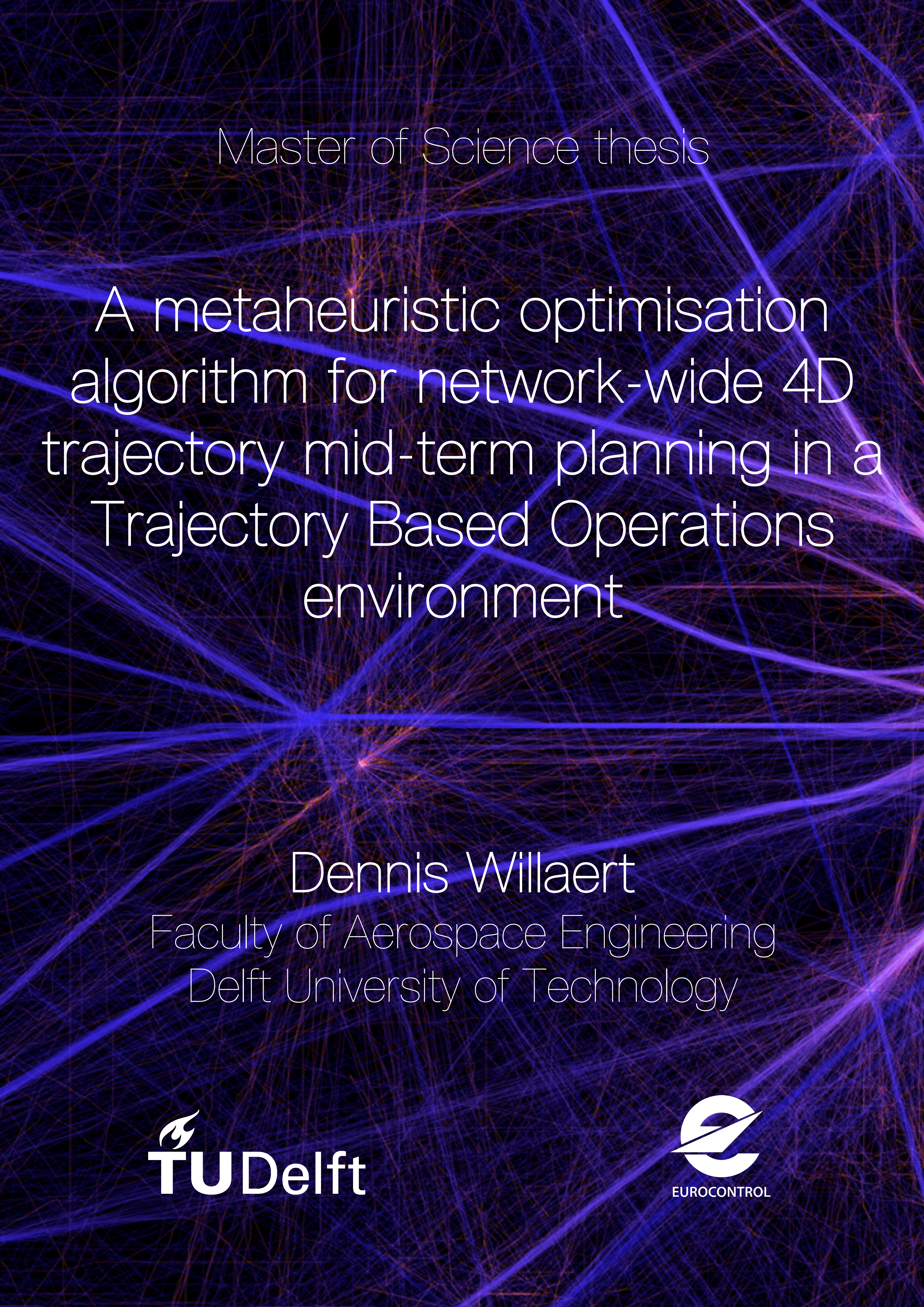

Master of Science thesis

A metaheuristic optimisation algorithm for network-wide 4D trajectory mid-term planning in a Trajectory Based Operations environment

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Master of Science Thesis

A metaheuristic optimisation algorithm for network-wide 4D trajectory mid-term planning in a Trajectory Based Operations environment

by

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In the long history of humankind
those who learned to collaborate and improvise most effectively have prevailed.

Charles Darwin

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List of Abbreviations

ANC	Air Navigation Commission
ANSP	Air Navigation Service Provider
APM	Aircraft Performance Model
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATMRPP	Air Traffic Management Requirements and Performance Panel
AU	Airspace User
AUO	Airspace User Operations
BADA	Base of Aircraft Data
CASA	Computer Assisted Slot Allocation
CDM	Collaborative Decision Making
CSV	Comma-Separated Values
DCB	Demand and Capacity Balancing
DDR2	Demand Data Repository 2
EUROCONTROL	European Organisation for the Safety of Air Navigation
FF-ICE	Flight and Flow Information for a Collaborative Environment
FIXM	Flight Information Exchange Model
FL	Flight Level
FOC	Flight Operations Centre
FPL	Flight Plan
ftfm	Filed Trajectory Flight Models
GA	Genetic Algorithm
GANP	Global Air Navigation Plan
GATMOC	Global Air Traffic Management Operational Concept
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILP	Integer Linear Program
LCC	Lambert Conformal Cone
NextGen	Next Generation Air Transportation System
NF	Network Function
NWTP	Network-Wide Trajectory Planning

SA	Simulated Annealing
SARP	Standards and Recommended Practices
SESAR	Single European Sky Air Traffic Management Research
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
TI	Trajectory Interaction
TID	Trajectory Interaction Detection
TIR	Trajectory Interaction Resolution
TMC	Trajectory Modification Cost
TS	Traffic Synchronisation
TSV	Tab-Separated Values
TV	Traffic Volume
UTC	Coordinated Universal Time
V&V	Verification and Validation
2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional
4DT	Four Dimensional Trajectory

List of Symbols

C	Grid cell
c_f	Fuel consumption
C_F^i	Alternative trajectory fuel costs of flight i
$C_{F,des}^i$	Desired trajectory fuel costs of flight i
C_{TM}	Trajectory modification costs
C_{TMD}	Delay trajectory modification costs
C_{TMF}	Fuel trajectory modification costs
d	Distance
d_H	Horizontal distance
d_V	Vertical distance
F	Fitness function
h	Height
i	Single flight trajectory i
I	Set of all flight trajectories
j	Single flight trajectory j
J	Set of all interacting flight trajectories
k	Amount of sampled coordinates on each trajectory
k^i	Waypoint of flight trajectory i
K_i	Set of all waypoints in flight trajectory i
M	Constant with order of magnitude larger than trajectory modification costs
N	Amount of aircraft within the network
n_d^i	Amount of possible delay slots of flight i
n_h^i	Amount of possible height levels of flight i
N_H	Minimum allowed horizontal separation distance
N_V	Minimum allowed vertical separation distance
p_d	Cost of delay
p_f	Fuel price
t	Timestamp
T^i	Set of all time stamps in flight trajectory i
$V_{H_{max}}$	Maximum horizontal speed
x	X-coordinate (Lambert Conformal Cone projection)
y	Y-coordinate (Lambert Conformal Cone projection)
δ_{ds}	Departure time shift step size
δh^i	Flight level change of flight i
δh_{max}^i	Maximum allowed flight level change of flight i
δ_{hs}	Flight level change step size
δt^i	Departure time shift of flight i
δt_{max}^i	Maximum allowed departure time shift of flight i
δ_{ts}	Time step between consecutive waypoints
λ	Longitude (WGS84 projection)
λ_0	Reference longitude (WGS84 projection)

ϕ	Latitude (WGS84 projection)
ϕ_0	Reference latitude (WGS84 projection)
ϕ_1, ϕ_2	Standard Parallels (WGS84 projection)
Φ_{tot}	Total amount of interacting trajectories
Φ^i	Interaction value of trajectory i

1

Introduction

The air transport industry is growing at a fast rate with forecasts indicating the global air traffic volume will double over the next 20 years [3]. To accommodate this growing air traffic in a safe and efficient way, an Air Traffic Management (ATM) paradigm shift from current Time Based Operations towards Trajectory Based Operations (TBO) is envisioned [4].

TBO entails the exchange, maintenance and use of consistent aircraft four dimensional trajectory (4DT) and flight information for collaborative decision-making (CDM) on the flight. Collaborative means involvement of the airspace user (AU) [5]. As a result the trajectory accuracy and predictability will increase which will allow for a more efficient and effective planning that could be performed earlier in time (compared to current Time Based Operations). This will increase the capacity.

This thesis addresses balancing flight efficiency and network stability in a TBO environment, which is a key research gap in the field of TBO [6]. Therefore, the aim of the work is to find a suitable network-wide trajectory planning (NWTP) mechanism which uses the full potential of the technical enablers and processes being implemented in a TBO environment to balance efficiency and stability.

This thesis report is structured as follows. First, a literature study is performed on the TBO concept, NWTP and efficiency/stability indicators in Chapter 2, followed by the research objective and questions in Chapter 3. Subsequently, the methodology and experimental setup are explained in Chapter 4 and 5 respectively. Afterwards, an elaboration is given on the results in Chapter 6, followed by a conclusion in Chapter 7. Finally, future work is stated in Chapter 8.

2

Literature Study

The thesis addresses NWTP in a TBO environment, to balance efficiency and stability. The purpose of this chapter is to get familiar with the topic of TBO, and to get an accurate overview of the state-of-the-art on NWTP in a TBO environment.

First, background information on TBO is given in Section 2.1, followed by an elaboration on NWTP in Section 2.2. Finally, efficiency and stability are defined on both individual flight and network level in Section 2.3. Subsequently, built on this knowledge a clear problem definition is formed in Chapter 3.

2.1. Trajectory Based Operations

With the goal of accommodating the growing air traffic in a safe and efficient way, the International Civil Aviation Organization (ICAO) developed the Global ATM Operational Concept (GATMOC) which entails the vision of the future integrated, harmonised and globally interoperable ATM system beyond 2025 [7]. Implementation of the GATMOC is performed by research and development initiatives such as the Single European Sky ATM Research (SESAR) in Europe [8], and the Next Generation Air Transportation System (NextGen) in the United States of America [9], who envision an ATM paradigm shift from the current Time Based Operations environment towards the TBO environment [4].

First the need for TBO is explained. Next the TBO characteristics are defined, followed by the improvements it brings. Finally the research gaps in the TBO field are given.

2.1.1. Need for change

The gaps of current ATM system which create the need for a paradigm shift towards TBO are as follows [5].

- Limited information is exchanged which causes inconsistencies in the AU's and air navigation service provider's (ANSP) planning.
- Voice clearances are not always included into automation and systems do not always share known information which could affect the trajectory prediction.
- No single, consistent view of the expected trajectory is maintained using the best-known information from all relevant ATM Concept Components such as the AU and ANSP.
- Due to the lack of a shared and collaboratively-obtained reference, decision making is either not informed by a trajectory or is based on locally managed, often inaccurate, information.

2.1.2. Characteristics

In order to fulfil the previously mentioned gaps of Time Based Operations, the characteristics of TBO are defined as follows according to ICAO, a specialised agency of the United Nations [5].

- TBO entails the sharing of trajectory info and provision of access to the most accurate 4DT (three dimensional space and time) data and its input, resulting in greater precision and predictability of the trajectories earlier in time unleashing additional capacity [10]. Figure 2.1 represents this characteristic of a TBO environment.
- TBO allows for globally consistent management of the trajectory info using CDM across the network, incorporating the AU's perspective [11].
- The agreed trajectory will be a unique reference for the flight by provision of a common intent to be achieved during execution of flight [12].

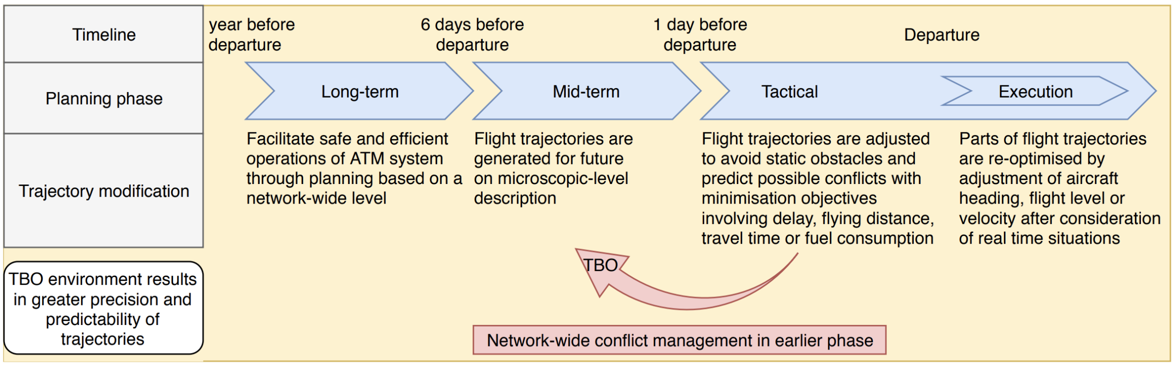


Figure 2.1: ATM planning timeline in TBO.

The TBO Concept [5] is the leading document used in this thesis. Other relevant ICAO information related to the TBO topic is depicted in Figure 2.2 [7] [13] [5] [14] [15].

Figure 2.2: Relevant ICAO documents in the field of TBO.

Essential to realise TBO is the increased level of automation of the ATM system [4]. Therefore, ground- and airborne-based technical enablers and infrastructure should be in place which allow accurate info derivation, sharing and CDM across the network, such as the System Wide Information Management (SWIM) [10].

2.1.3. Improvements

TBO will enhance ATM processes starting at the point an individual flight is being planned through flight execution to post flight activities, reducing potential trajectory interactions and resolving upcoming network and system demand-capacity imbalances earlier in time compared to Time Based Operations. The expected benefits of TBO implementation according to [5] are listed below.

- Improved trajectory accuracy and consistency.
- Improved predictability and system-wide performance.
    - Maximised throughput to use available system capacity.
    - Reduced use of vectoring and holding.
    - Improved fuel efficiency and fuel-loading decisions.
    - Improved block time scheduling.
- Maximised use of airport and airline resources through gate management and operations management.

2.1.4. Research gap

On a conceptual level, the ICAO ATM Requirements and Performance Panel (ATMRPP) expert group has developed a mature draft of the TBO Concept [5]. However, as described in the ICAO Working Paper [6], several research gaps have to be bridged in order to progress towards a mature TBO environment. One of the key research gaps concerns the question on how to balance individual flight efficiency/stability and network efficiency/stability in a TBO environment.

The main goal of the work is to find a suitable NWTP mechanism which uses the full potential of the technical enablers and processes being implemented in a TBO environment to balance efficiency an stability. The overarching goals for implementation of TBO are the improvement of flight efficiency in stable network [8]. The proposed NWTP mechanism should therefore contribute to this goal. The next section elaborates on the NWTP, followed by a section which provides more information on efficiency and stability.

2.2. Network-wide 4D trajectory planning

An NWTP is used to balance efficiency and stability. In this section, first the the need for a TBO environment specific NWTP is provided. Subsequently, the characteristics and scope of an NWTP is given. Finally, specific information on existing literature regarding the mid-term planning process of the Network Function (NF) in a TBO environment is provided.

2.2.1. Need for change

In current Time Based Operations in Europe, the Air Traffic Flow Management (ATFM) performs the NWTP before departure on macroscopic level, which means only satisfaction of sector capacity constraints are taken into account without considering the 4DTs in detail [16]. From days before departure onwards until departure, the ATFM performs the network-wide planning using the Computer Assisted Slot Allocation (CASA) algorithm.

From the demand side, the ATFM receives all FPLs (FPL) from the different AUs. From the capacity side, the ATFM receives the capacity constraints for the different sectors or traffic volumes (TV) within the network from the local ANSP. If demand is higher than capacity for a certain TV, the CASA algorithm regulates the TV and allocates time slots to the flights entering the TV. If a flight crosses several regulated TVs, the system picks the most penalising regulation in terms of delay, which is then used for further calculations. Afterwards, it calculates back the new calculated take-off time which includes the assigned ATFM delay and sends it back to the AUs. As soon as a flight departs, ATM services are not provided by the ATFM anymore, but by the local ANSPs where the Air Traffic Controllers (ATCos) manage their sector on a microscopic level [17].

The main limitation of the current network planning algorithm, CASA, is its limited amount of imbalance resolution strategies. Only departure delay is considered, while other resolution methods such as flight level (FL) changing and vectoring could also be considered in a TBO environment with more accurate 4DT info before flight [18]. Furthermore, only macroscopic flows and demand-capacity imbalances are scrutinised in the planning phase before departure. Even though network-wide microscopic trajectory planning without pre-structured network is possible in a TBO environment [19]. Therefore, the aim is to find a more optimal NWTP mechanism for a TBO environment.

2.2.2. Characteristics

A high level schematic representation of the stakeholders involved in trajectory planning in TBO, is depicted in Figure 2.3, according to the novel TBO Concept which is based on the GATMOC [5] [7]. In this figure one could identify the five groups of concept components and the tasks they perform in each planning phase, based on the definitions stated in GATMOC [7].

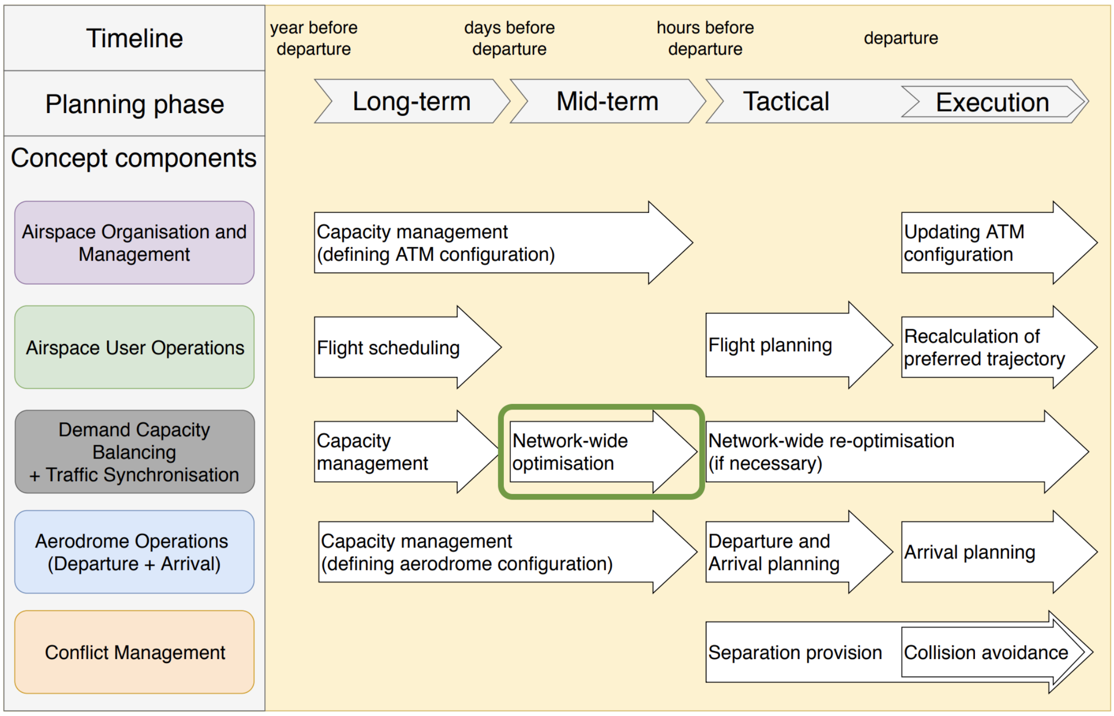


Figure 2.3: Trajectory planning processes by concept component in TBO.

CDM processes take place among the concept components to decide and change the agreed 4DT within the defined ATM configuration constraints [11]. Furthermore, the GATMOC encloses that Demand Capacity Balancing (DCB) or ATFM and Traffic Synchronisation (TS) or Air Traffic Control (ATC) will become integrated in the future TBO environment. This could be interpreted as a switch from current process where ATFM is mainly responsible for development of the network plan and ATC is mainly responsible for execution of that plan, towards a process where both entities will work progressively together on development, updating and execution of the plan.

In order to produce an in-depth result within the given thesis timeframe, the scope of the thesis is limited to one planning process. As the thesis is conducted at the European Organisation for the Safety of Air Navigation (EUROCONTROL) in Brussels, which manages the mid-term network-wide planning within the European sky, the scope is narrowed to the mid-term NWTP process taking place in the integrated ATFM/ATC concept component. This process is encircled in green in Figure 2.3.

The mid-term phase lasts from days before departure until hours before departure [20]. For the thesis, it is assumed that in this phase, all desired FPLs are filed by the AUs in order to be taken into account in the NWTP process. Furthermore, it is assumed no flights have departed so trajectories could be changed entirely. An elaboration on the mid-term planning process is given in the next part.

2.2.3. Mid-term planning process in TBO

Figure 2.4 provides a schematic overview of the mid-term planning phase in TBO based on the ICAO TBO Concept [5]. For the sake of simplicity, the Flight Operation Center (FOC) and the AU are combined into the Airspace User Operation (AUO) concept component. Furthermore, the DCB and TS concept component are combined into the NF concept component. In reality, however, the two actors in each combination have several processes going on in between them mutually.

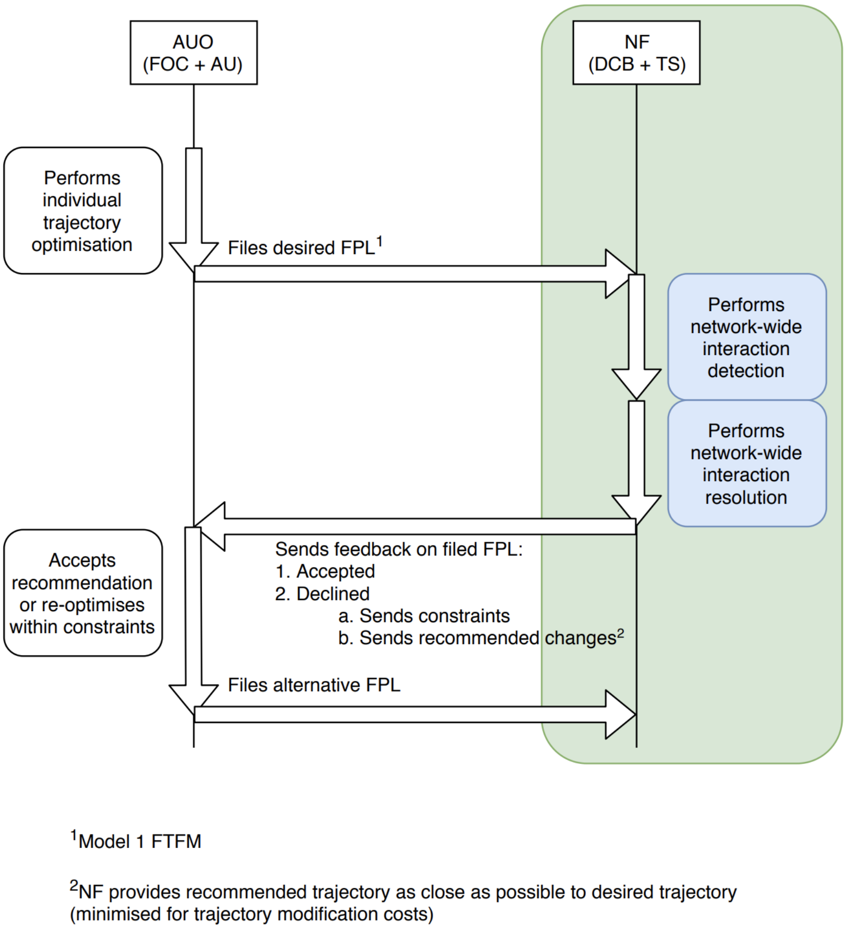


Figure 2.4: Mid-term planning process in TBO.

As shown in the figure, the AUO performs the individual trajectory optimisation and files its desired FPL. As soon as the NF receives all individually optimised FPLs, the NF detects all trajectory interactions (TI) on a network-wide level. After the trajectory interaction detection (TID) process, the NF resolves the TI on a network-wide level in the most optimal way. Most optimal is defined in Section 2.3.

Afterwards, the NF sends feedback to the AUO. This feedback could either be FPL acceptance, or FPL decline together with the violated constraints (e.g. airspace violations) and a recommended non-interacting alternative trajectory. The AUO subsequently has the chance to accept the recommended alternative or to re-optimise themselves within given constraints. Afterwards, the AUO sends back the alternative FPL to the NF. The NF checks again on TI and sends feedback to the AUO, and so on.

In terms of constraints, the scope will be limited to TIs. In reality, additional capacity constraints for example due to military airspace closures or bad weather exist, of which the effect on the NWTP could be investigated in future work.

This thesis will focus on the NF Concept Component. Two main NF processes to balance efficiency and stability as indicated in blue in Figure 2.4 exist. First the TID process, followed by the trajectory interaction resolution (TIR) process. State of the art within the field of both processes is given in the subsequent parts of this subsection.

Trajectory interaction detection

An interaction of two trajectories in mid-term planning phase occurs when two or more aircraft compete for the same airspace at the same period of time. In the rest of the thesis, a TI is defined as a flight which competes for at least one airspace at one period of time along its trajectory with at least one other aircraft, during planning phase. Therefore, due to uncertainties such as for example weather changes or unforeseen ground delay, network changes could occur and re-optimisation could be needed in later stages. It is different from a conflict situation, as the latter corresponds to a minimum separation violation of at least two aircraft during execution phase.

Several separation conditions could be defined such as distance between trajectories, time separation, topology of trajectory intersections [1]. For the sake of simplicity, the scope of the thesis is limited to the en-route phase. During this phase the horizontal separation distance (N_H) of $5NM$ and vertical separation distance (N_V) of $1000ft$ will be used, as they correspond to the ICAO minimum separation standards [21]. Figure 2.5 indicates the minimum separation cylinder around each aircraft.

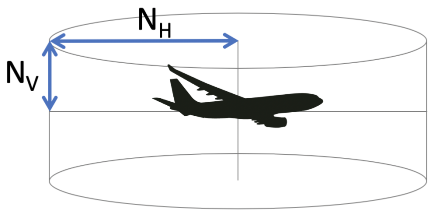


Figure 2.5: Trajectory interaction cylinder.

In order to evaluate the interactions between aircraft, a TID method has to be defined. Three methods are found in previous literature, namely the pairwise comparison method, the probabilistic method, and the grid-based method. These methods are explained in detail below.

Pairwise comparison method

A pairwise TID algorithm compares the aircraft position along its trajectory with the other aircraft in the network for each timestamp. An interaction occurs when the minimum separation cylinders as shown in Figure 2.5 of two aircraft overlap. This method is being used in [22] and [23]. The amount of comparisons equals $(k \cdot N)^2$ where k is the number of sampled coordinates on each trajectory and N is the number of aircraft in the network. Therefore, the method is computationally exhaustive and only effective when considering a small number of aircraft. As in this thesis, the network will be optimised on continental level with thousands of flights consisting of hundreds of waypoints, this method is not suitable for TID within limited time.

Probabilistic method

The probabilistic TID method first generates a complete set of possible future trajectories, each weighted by a probability of occurring. Afterwards, the trajectories are propagated into the future to determine the probability of an interaction. This method is being used in [24] and [25]. Similar to the pairwise comparison approach, this method is only effective when dealing with a small number of aircraft due to exhaustive computations, and is therefore not suitable for this thesis.

Grid-based hash table method

The grid-based hash-table method as used in [1], [26] and [27] is an approach that could be used for a large number of aircraft. As seen in Figure 2.6 the four dimensions are three dimensional (3D) space and time. The size of each cell is defined by the minimum separation requirements N_H and N_V as given Figure 2.5, and by the chosen time step. In each of the occupied 4D cells a list of aircraft within the cell is stored for quick calculations when trajectories are modified. For each non-empty cell, the neighbouring cells are checked to detect potential conflicts. Considering the computationally expensive nature of the planning problem (due to network-wide planning) in this thesis, it could be concluded this method is the most promising to use. Therefore, an elaboration on the methodology is given in Chapter 4.

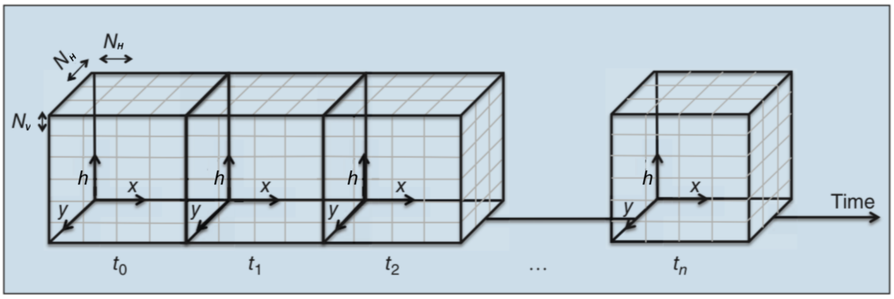


Figure 2.6: 4D grid for trajectory interaction detection [1].

Trajectory interaction resolution process

After the TID process, the interacting trajectories are modified to resolve the interactions. Finding the optimal resolutions in a capacity-limited airspace given thousands of flights is a computationally difficult task. Therefore, the right optimisation method has to be selected. In [28] the traditional integer linear programming (ILP) method is compared to two intelligent optimisation algorithms, simulated annealing (SA) and genetic algorithms (GA) based on solution quality and runtime. On one hand, ILP provided the best results in both solution quality and runtime. On the other hand, ILP runtime significantly changes based on the difficulty of the problem while SA and GA indicate a more constant runtime independent of the difficulty of the problem. As ATM network planning has the criterion that a solution must be provided in a guaranteed timeframe, the intelligent optimisation algorithm proves to be the better suitable option.

Furthermore, the intelligent optimisation algorithms are better equipped to handle uncertainty and are more amendable for future online approaches where optimisation tools are continually solving, and the best solution could be pulled from the tool at any time [29]. In terms of both solution quality and runtime, the SA outperforms GA by a small difference [30] [28]. However, the GA computing could be distributed which would result in significant solution quality improvement and runtime decrease, likely outperforming the SA approach [31]. GA is used in state of the art [20], [18] and [32]. This method is further explained in Chapter 4.

The decisions variables of the optimisation problems are the allowed flight manoeuvres. Different strategies could be used to resolve TIs. As done in current Time Based Operations, the departure time could be tuned as seen in [18]. Other manoeuvres are FL changes [33] or flight route adjustments [34]. Additionally, flight speed could be changed [35]. However, according to [1] this approach is a computationally extensive task not suitable for a large-scale problem. Lastly, a combination of the above could be used as in [20] and [1]. A combination of the above, namely departure time change and FL change is chosen and elaborated in Chapter 4.

2.3. Efficiency and stability

The gap to be bridged in this thesis is how to balance individual flight efficiency/stability and network efficiency/stability in TBO [6], which will be done by an NWTP. Therefore, a definition has to be given to what is meant with efficiency and stability, and which indicators could be used to measure it, both from an individual flight perspective as well as from a network perspective.

A stable network is a network that converges towards an optimal solution. An optimal network solution could be defined as a set of efficient flight trajectories (efficient in terms of costs), which are not interacting with each other. Therefore, a balancing mechanism should be able to guarantee a minimum stability (e.g. no TIs), while it maximises efficiency (e.g. reducing fuel and delay costs).

In reality, uncertainties (such as for example weather changes or take off time changes due to technical failures) affect the planning process. One could take these uncertainties into account by using probabilities of occurrence (which will change over time) for each actor within the ATM system. For example, one could be aware a couple of days before occurrence that a storm would pass over a country without knowing the exact location yet. The more one evolves towards time of expected occurrence, the more accurate information one receives about the specific location, and as a result the uncertainty will lower. In practice, there would be a point in time during planning phase where enough information would be received regarding the uncertainties in order to make decisions on for example rerouting or departure delay of flight. This point in time could be different for each element within the ATM system. For example, a flight crossing an often stormy area could have more uncertainty than a flight crossing a non-stormy area. Uncertainties are out of the scope of this thesis, but could be investigated in future work.

The indicators found in existing literature are structured into a 2 by 2 matrix. On one axis, the matrix indicates whether it concerns efficiency or stability. On the other axis, it shows it is either an individual flight performance metric or a network metric. This matrix of indicators including their references, are shown in Table 2.1. Both network and individual flight indicators are elaborated below.

Table 2.1: Efficiency and stability indicator matrix.

	Flight efficiency	Stability
Individual	Delay cost / trajectory [35] [20] Delay time / trajectory [18] [36] [1] [20] [37] Fuel consumption cost / trajectory [35] [36] Total costs / trajectory (flight trajectory, ground holding, airborne holding, FL change, time of arrival tuning) [20] Total costs / trajectory (fuel, delay, navigation, maintenance) [38]	FL changes / trajectory [20] Vector changes / trajectory [20] Route extension / trajectory [1] Risks (weather, de-icing, terrain proximity, low fuel, depressurisation, emergency, manoeuvre hazard) [38]
Network	Total network delay cost [20] Total network delay time [18] Total network fuel consumption cost [35]	Number of conflicts [35] [18] [1] [27] [20] [37] Intensity (separation distance) [35] Congestion (flight passing rate) [18]

2.3.1. Network indicators

As discussed in [5], one of the key characteristics of TBO is the incorporation of the AU perspective into decision making processes. As discussed in the next steps description of [1] the best efficiency indicator to reflect this characteristic is trajectory modification costs (TMC). The reasoning behind this entails as follows. Most airlines strive to minimise costs [39]. Considering this statement, it is assumed airlines file the FPLs they desire to fly, and which are the most cost-efficient for them. Therefore, if alternative trajectories have to be flown to resolve trajectory interactions, they should be as close as possible to the initial filed FPLs. This could be done in the NF by defining a minimisation problem for network TMC between filed flight trajectories and alternative flight trajectories. Another benefit of minimising costs is that different cost sources could be expressed in the same unit, which allows to compare multiple TIR strategies against each other. Significant cost sources are fuel costs and delay costs [40]. These are considered in this thesis. To guarantee network stability, trajectory interactions should be limited [18] [1]. Additionally, [35] considers network intensity in order to reduce ATCo workload.

2.3.2. Individual flight indicators

The individual flight efficiency indicators are - analogue to the network efficiency indicators - related to costs. Most indicators are fuel consumption related costs per flight or delay related costs per flight [18] [35] [20]. The fuel consumption costs per flight could for example be costs due to vectoring or a FL change. Individual flight stability indicators are limitations on the aircraft resolution manoeuvres. For example, amount of FL or vector changes per flight [20] [27].

2.4. Conclusion

This section wraps up the key takeaways and gaps from existing literature, so research objective and questions could be defined. Introduction of TBO will allow for a more optimal NWTP mechanism (in mid-term planning phase) to balance efficiency and stability both on individual and network level [5]. TBO entails sharing of accurate 4DT info, and allows for CDM across the network. Therefore, the AU perspective could be incorporated into network-wide planning. Agreed trajectories are unique references for flights.

NWTP consists of two main processes, namely the TID process and the TIR process. To cover the former process, the grid-based method suitable for large data-sets could be used, as described in [27]. To cover the latter process, a GA as optimisation procedure is the most promising option due to the potentially fast and constant runtimes it brings [18], and the ability to scale computation, with increased solution quality or decreased runtime as a result [31]. Two main gaps in existing research covering this NWTP based on GA could be defined.

First, no AU perspective is taken into account in current NWTP processes proposed in literature. To close this gap, the objective function of the NWTP should optimise the variable which covers the AU perspective. AUs could have different objectives, but most airlines try to minimise costs when flying from A to B. In this thesis, it is assumed that the initial filed FPL is the most optimal from an AU perspective [1]. Therefore, the objective of the optimisation problem is to minimise TMC with respect to the initial filed FPL. The costs considered are limited to fuel costs and delay costs. Network efficiency is measured by total network TMC. However, while minimising TMC the network should remain stable. A stable network is a network that converges towards an optimal solution. An optimal network solution could be defined as a set of efficient flight trajectories (minimum TMC), which are not interacting with each other (no TIs). In reality, uncertainties (such as weather uncertainties) will affect the planning, but this will remain out of the thesis scope.

In order to resolve the TI, modifications to the trajectories are made. This brings us to the second gap to be closed in the thesis. No full potential of the 4DT information is used in existing literature covering NWTP by GA [18]. The approach of [18] is limited to a single TI resolution strategy, namely departure delay (change in time dimension). As TBO allows for multiple TI resolution strategies, in this thesis a situation with two TI resolution strategies is tested. More specifically a combination of departure delay [18] and FL change [35] manoeuvres (change in time and space dimension) is used.

Individual flight stability is measured by the limitations of the TI resolution strategies (maximum allowed departure delay and maximum allowed FL change) per flight. Individual flight efficiency could be measured by the average TMC per flight.

In reality, uncertainties (such as weather changes or take off time changes due to technical failures) affect the planning process. These uncertainties are out of the thesis scope, but could be investigated in future work.

3

Research Objective and Questions

This chapter entails the research objective in Section 3.1 and research questions in Section 3.2. These questions are answered in the subsequent chapters of the report.

3.1. Research objective

Introduction of TBO will allow for a more optimal NWTP mechanism to balance efficiency and stability. Current state of the art literature addressing NWTP considers the computationally fast genetic algorithm optimisation method [18].

The research objective is to contribute to the network-wide trajectory planning suitable in Trajectory Based Operations by minimising for network trajectory modification cost to include the airspace user's perspective, while adding decision variable limitations to ensure individual flight stability, and limiting the amount of allowed trajectory interactions to ensure network stability. Furthermore, multiple trajectory interaction resolution strategies (departure delay and flight level change) should be included. The research objective is achieved when the proposed mechanism has been modelled, simulated, and evaluated.

3.2. Research questions

Based on the research objective, the defined research question is as follows.

Is it possible to balance efficiency and stability in a Trajectory Based Operations environment by a network-wide 4D trajectory planning mechanism based on genetic algorithm which minimises network trajectory modification costs, and allows for multiple trajectory interaction resolutions (departure delay and flight level change)?

This research question is broken down into sub-questions. When all sub-questions are answered, a conclusive answer can be formed on the research question.

I Regarding the modelling of the NWTP problem:

  (a) Which method could be used to convert the continuous space into an equivalent discrete space?
  (b) What are the objective function, constraints, and decision variables of the optimisation problem and how is it mathematically modelled?
  (c) What is the genetic representation of the mathematical problem and how is the mathematical model converted?

   (d) What are the limitations of the defined mathematical model w.r.t. the TBO concept?

II Regarding the simulation of the NWTP mathematical model:

   (a) What is the difference between current and TBO flight plan information?
   (b) Which assumptions have to be made to use current flight plans for future TBO scenarios?
   (c) What is the selected time window and traffic volume of the flight plan dataset?
   (d) What data cleaning steps have to be performed to use the flight plan dataset?
   (e) What is the allowed runtime and which assumptions have to be made to stay within this limit?

III Regarding the evaluation of the simulation:

   (a) Which indicators measure individual flight efficiency and stability? How do they compute results?
   (b) Which indicators measure network efficiency and stability? How do they compute results?
   (c) What is the influence of the trajectory interaction resolution strategies, both individual and combined, in terms of performance?
   (d) Is the quality of the solution within the allowed runtime sufficient to be used in TBO?
   (e) What modifications could be added to the proposed NWTP to increase performance?

4

Methodology

In Section 4.1 of this Chapter, an overview is given on the mid-term planning and simplifications are stated. Subsequently, Section 4.2 entails the determination of the 4DTs. Section 4.3 covers the TID process. Finally, Section 4.4 elaborates on the TIR process.

4.1. Mid-term planning overview

The illustration of the full process within the NF is shown in Figure 4.1. First the desired 4DTs are retrieved from the filed FPLs elaborated upon in Section 4.2. Afterwards, the interactions between trajectories are detected using the grid-based method as explained in Section 4.3. The outcome of this step is a set of interacting 4DTs and a set of non-interacting 4DTs.

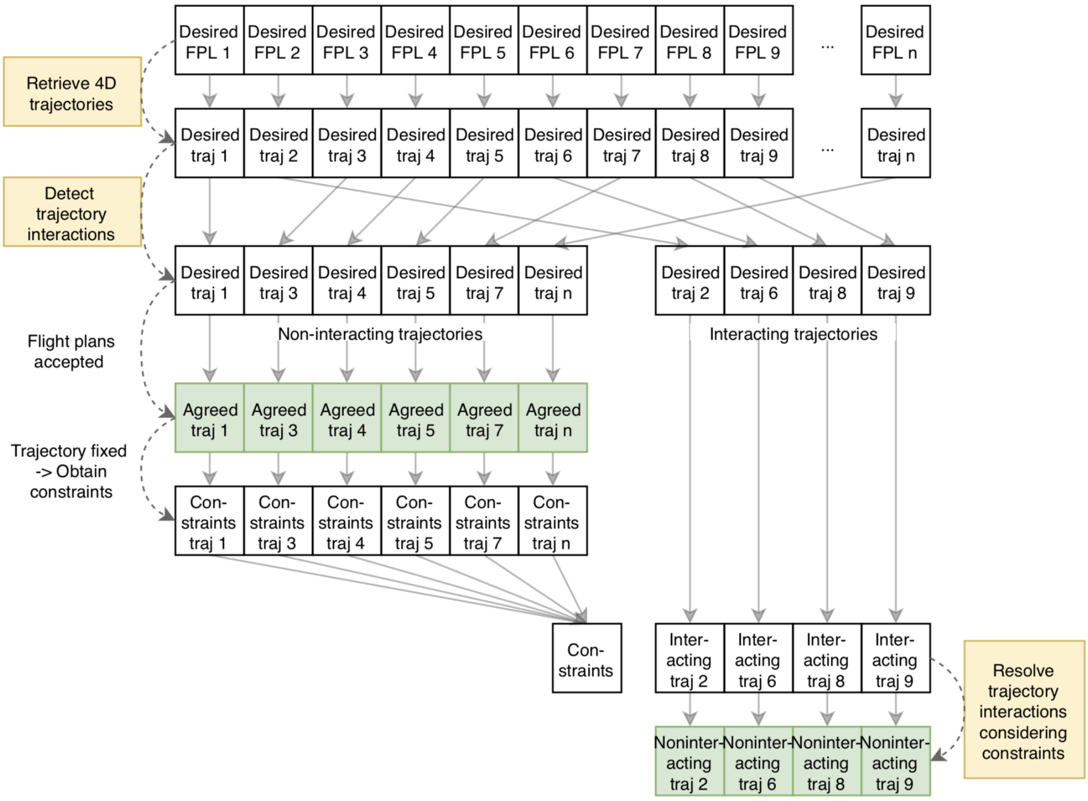


Figure 4.1: Network-wide trajectory planning process.

Both sets will be used in the subsequent step of the process explained in Section 4.4, namely the TIR. The set of coordinates of the non-interacting 4DTs will be used as fixed constraints in the network optimisation problem, while the set of interacting 4DTs will be optimised to resolve the interactions between them with a minimum amount of network trajectory modification costs. The outcome of this step is a complete set of non-interacting 4DTs. The assumptions and simplifications to solve the network optimisation problem are given in the next subsection.

4.1.1. Assumptions and simplifications

The assumptions and simplifications in this subsection are structured into three categories: FPL related, efficiency and stability related, and Base of Aircraft Data (BADA) related topics.

Flight plan

- AUs file what they want to fly and fly what they filed. This is one of the targeted outcomes of TBO. Currently airspace users often file different FPLs which are not intended to be followed.
- All FPLs are received in advance and could be taken into account for optimisation. In reality, flights could be submitted just before departure.
- The scope is limited to the en-route phase. According to [41], this phase starts when leaving the $50NM$ radius around the departure airport and ends when entering the $50NM$ radius around the arrival airport as shown in Figure 4.2. Therefore, the route points within the rings are discarded. In reality, the start and end of this phase depends on the FPL and aircraft type.

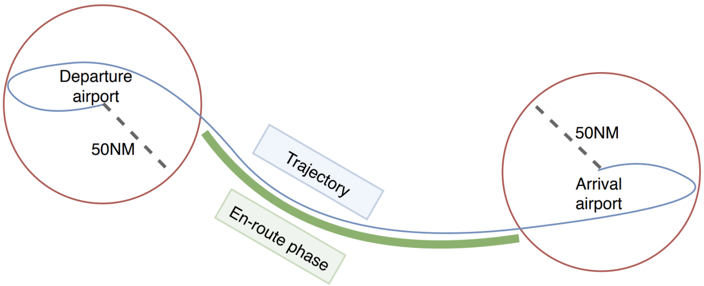


Figure 4.2: Illustration of en-route scope definition.

- Linear interpolation is used between route points. In reality, it is not possible to fly a perfectly linear route between points, and often the linear route is not optimal.

Efficiency and stability

- As previously explained in Subsection 2.2.3, in this thesis a TI is defined as the situation in planning phase, when two or more aircraft compete for the same airspace at the same period of time. In reality, additional constraints such as airspace closures for military purposes or bad weather exist.
- Trajectory costs are limited to fuel costs and delay costs. In reality, other costs such as route charges and maintenance costs are also taken into account.
- Trajectory modification possibilities are limited to a departure time shift and an en-route FL change. In reality, route changes and airspeed changes could be introduced additionally to resolve TIs.

BADA aircraft performance model

- Nominal aircraft mass level and airspeed is considered for each flight. In reality, the mass level and airspeed varies from flight to flight, and influences the optimal flight profile and fuel consumption. Furthermore, no weather effects such as winds are taken into account.
- All aircraft are assumed to be in cruise mode. In reality, the aircraft will be in different modes during a flight such as climb and descent mode.
- If an aircraft is not recognised in the BADA database, the Aircraft Performance Model (APM) of an Airbus A320 is considered. In reality, the aircraft which are not in the database are often special aircraft types, and therefore very different from the A320. As a consequence, they could have a different APM.

4.2. Determination of 4D trajectories from flight plans

FPLs will evolve in a future TBO environment. As explained in Chapter 2, the ICAO Flight and Flow Information for a Collaborative Environment concept provides the globally harmonised process for planning and for providing consistent flight information [14]. Implementation of the concept eliminates or reduces the limitations of the present FPL. The Flight Information eXchange Model (FIXM) is the data model for the exchange of flight data in a future TBO environment [32]. The FPLs used in future TBO environment, often referred to as eFPL, will provide more detailed 4DT information, such as more waypoints and more information like wind speed, wind direction and temperature at each waypoint.

In this thesis, routes of FPLs will be used. A route is a string of waypoints describing the path. The points are no more than 30 minutes flying time or $200NM$ apart from each other. Furthermore points are included where a change of speed, level, track or flight rules is planned. The points are listed by a coded designator (such as MAY) and a 7 or 11-character representation of their coordinates (i.e. 46N078W, 4620N07805W). The coordinates are given in the WGS84 coordinate system.

Transformation of coordinates into Lambert Conformal Cone projection

In order to use the route points for further calculations, the latitude and longitude coordinates are transformed into the Cartesian (x,y) coordinates by a Lambert Conformal Cone (LCC) projection. This is the projection used for aeronautical geocentric translations above Europe as a straight line drawn on a LCC projection approximates a great-circle route between endpoints for typical flight distances [42] [43]. A representation of the projection is given in Figure 4.3. The altitude of the aircraft is represented by the z-coordinate, h. This coordinate remains unchanged during transformation. It is assumed that the filed FPL is the desired FPL most optimal for the airliner. Consequently, it is assumed that the FL and altitude profile of the discretized 4DT is optimal.

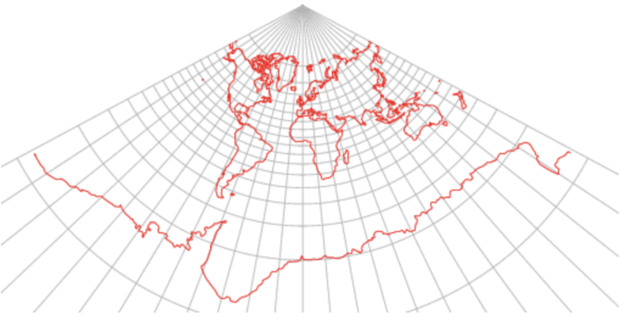


Figure 4.3: Lambert Conformal Conic projection [2].

Using Equations 4.1 and 4.2, the longitude (λ) and latitude (ϕ) coordinates from a spherical datum could be transformed into the LCC projection coordinates x and y. λ_0 is the reference longitude, ϕ_0 the reference latitude, and ϕ_1 and ϕ_2 the standard parallels.

$$x = \rho \sin\left[n\left(\lambda - \lambda_0\right)\right] \tag{4.1}$$

$$y = \rho_0 - \rho \cos\left[n\left(\lambda - \lambda_0\right)\right] \tag{4.2}$$

Where

$$n = \frac{\ln\left(\cos\varphi_1 \sec\varphi_2\right)}{\ln\left[\tan\left(\frac{1}{4}\pi + \frac{1}{2}\varphi_2\right)\cot\left(\frac{1}{4}\pi + \frac{1}{2}\varphi_1\right)\right]} \tag{4.3}$$

$$\rho = F \cot^n\left(\tfrac{1}{4}\pi + \tfrac{1}{2}\varphi\right) \tag{4.4}$$

$$\rho_0 = F \cot^n\left(\tfrac{1}{4}\pi + \tfrac{1}{2}\varphi_0\right) \tag{4.5}$$

$$F = \frac{\cos\varphi_1 \tan^n\left(\frac{1}{4}\pi + \frac{1}{2}\varphi_1\right)}{n} \tag{4.6}$$

4.3. Trajectory interaction detection

Figures 4.4 and 4.5 illustrate situations with three trajectories in the horizontal plane. In Figure 4.4 the protection volume around point $P_{2,2}$ of trajectory 2 (indicated in green) is not violated. Therefore, the binary value of Φ^B is zero. Figure 4.5 indicates the infringement of the protection volume of Trajectory B by two other trajectories A and C. Therefore, the binary value is 1.

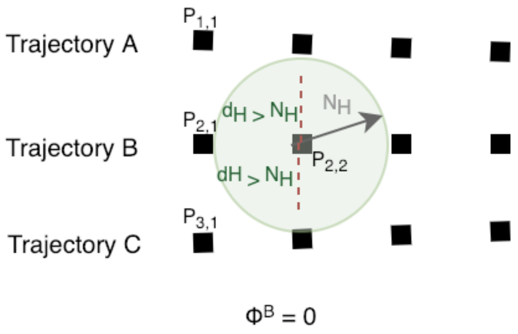


Figure 4.4: Example of a non-interacting trajectory.

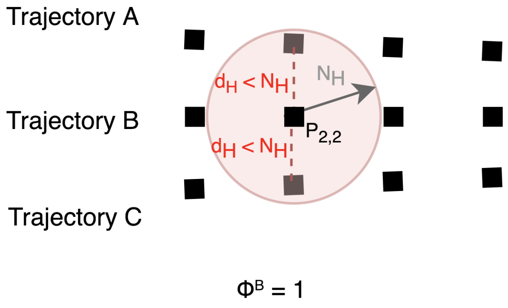


Figure 4.5: Example of an interacting trajectory.

Φ^i of trajectory i equals either 0 if not interacting or 1 if interacting with other trajectories within a given set of trajectories I. Equation 4.7 defines the amount of interacting trajectories Φ_{tot} for a given set of trajectories.

$$\Phi_{tot} = \sum_{i \epsilon I} \Phi^i \tag{4.7}$$

Grid-based hash table method

As discussed in Chapter 2.2, the grid-based hash-table method is selected to avoid time-consuming pair-wise comparisons [27] when dealing with a large number of trajectories. The first step of this method is to discretize the airspace into a four-dimensional grid, as indicated in figure 2.6. The grid is illustrated as a time series of 3D grids which is sampled with discretization time step $\Delta t = t_n - t_{n-1}$. The size of each cell in the 3D grid is defined by the minimum separation requirements horizontally (N_H) and vertically (N_V) as given in Figure 2.5.

The time step of the grid corresponds to the time step between trajectory points. This time step should be sufficiently small such that each trajectory has at least one sample in each unique cell it passes. The size therefore depends on the maximum possible aircraft horizontal and vertical speeds. In the horizontal plane level, the worst case scenario occurs when two aircraft follow parallel trajectories separated by a distance (d) less than or equal to the horizontal separation norm (N_H) at maximum horizontal speed ($V_{H_{max}}$) with the aircraft flying in opposite directions. In the vertical plane, the worst case scenario happens when an aircraft is climbing at max rate of climb, while another aircraft is descending at max rate of descent. Taking into account the fastest passenger aircraft both horizontally and vertically, a sampling time step of $20s$ could be considered [44].

If there are no sufficient points between two subsequent coordinates of a trajectory as given in the FPL, linear interpolation is performed. The discrete points between the waypoints k_n^i and k_{n+1}^i are linearly interpolated using Equation 4.8, for each time stamp $t = t_n + m * \delta_{ts}$ with δ_{ts} being the time step parameter between waypoints, and m a value in range $\{0, 1, ..., (t_{n+1} - t_n)/\delta_{ts}\}$. This equation provides the interpolation for the x value in time t. However, the same equation is used for values y and h.

$$x = x_n + (t - t_{n+1}) \frac{x_{n+1} - x_n}{t_{n+1} - t_n} \tag{4.8}$$

For each 4D coordinate $k^i(x^i, y^i, h^i, t^i)$ of each trajectory i, a corresponding grid cell $C_{u,v,w,t}$ is identified. Subsequently, each surrounding cell is identified. 3^3 (= 27) cells in total need to be checked. If a cell and its neighbouring cells is occupied by more than one aircraft at a certain time stamp (t), the horizontal (d_H) and vertical distance (d_V) between the two corresponding trajectories i and j are calculated using Equation 4.9 and 4.10, respectively.

An interaction between two flight trajectories (i, j) where $i \neq j$ within the set of all trajectories I occurs, when the horizontal distance ($d_H^{i,j}$) between at least one of their trajectory waypoints k^i, k^j from the set of trajectory waypoints K^i, K^j for $t \in t^i \cap t^j$ is smaller than the minimum allowed horizontal separation distance N_H, and the vertical separation distance ($d_V^{i,j}$) is smaller than the minimum allowed vertical separation distance N_V. The horizontal and vertical distance between two trajectory waypoints is calculated using Equation 4.9 and 4.10, respectively. The output of this step is a set of interacting flights J, which includes flights which interact with another flight within the set, at at least one waypoint among their trajectories.

$$d_H^{i,j} = \sqrt{(x^i - x^j)^2 + (y^i - y^j)^2} \quad \forall t^i = t^j \tag{4.9}$$

$$d_V^{i,j} = h^i - h^j \quad \forall t^i = t^j \tag{4.10}$$

Finally, in each of the 4D cells, a list of aircraft occupying the corresponding cell is stored. This hash-table data structure allows to quickly detect the number of interactions when trajectories are modified, without having to check the trajectories which are not modified and are not affected by other modified trajectories, again. For each non-empty cell, the neighbouring cells are checked to detect potential conflicts.

4.4. Trajectory interaction resolution

After detection of the TIs, the objective of the next step in the network-wide trajectory planning process is to resolve the TIs. The objective is to minimise trajectory modification costs. The decision variables are departure delay and FL change. The trajectory modification costs are the difference in costs between flying the desired trajectory according to the filed FPL, and flying the alternative trajectory to avoid a TI. In this Section, first the mathematical model is described, followed by an elaboration on the GA optimisation mechanism.

4.4.1. Mathematical model

The objective is to determine the optimal values for the decision variables, namely departure time shift (δt^i) and FL shift (δh^i) for each trajectory i in set of interacting flights J to minimise the amount of TIs for each flight i in set of all flights I in the most cost-efficient manner. The decision variables reflect the allowed resolution manoeuvres to resolve the TIs. The objective function is given in Equation 4.11. This objective function is subject to the constraints given in Equations 4.12 - 4.13.

$$\min \quad F(\delta h, \delta t) = C_{TM}(\delta h, \delta t) + \Phi_{tot}(\delta h, \delta t) \cdot M \quad \forall i \in I \tag{4.11}$$

$$\text{s.t.} \quad \delta t^i \in \{0, \delta_{ds}, ..., (n_d^i - 1)\delta_{ds}, n_d^i \delta_{ds}\}, n_d^i = \delta t_{max}^i / \delta_{ds} \tag{4.12}$$

$$\delta h^i \in \{0, \delta_{hs}, ..., (n_h^i - 1)\delta_{hs}, n_h^i \delta_{hs}\}, n_h^i = \delta h_{max}^i / \delta_{hs} \tag{4.13}$$

$C_{TM}(\delta h, \delta t)$ in the objective function 4.11 are the trajectory modification costs. As shown in Equation 4.14 this consists of two main parts, namely the delay trajectory modification costs $C_{TMD}^i(\delta t^i)$ and fuel trajectory modification costs $C_{TMF}^i(\delta h^i)$.

$$C_{TM}(\delta h, \delta t) = \sum_{i \epsilon I} \left(C_{TMD}^i(\delta t^i) + C_{TMF}^i(\delta h^i) \right) \tag{4.14}$$

The delay trajectory modification cost ($C_{TMD}^i(\delta t^i)$) as given in Equation 4.15 is calculated by multiplying the departure time shift or delay (δt^i) with the cost of delay (p_d). The cost of delay is extracted from a study which investigates the European airline delay cost reference values [45]. These values are also used by EUROCONTROL to assess ATM performance [40]. The delay time is the difference between the departure time of the desired trajectory and the departure time of the alternative trajectory. Differences in airspeed changes between the alternative trajectory and the desired trajectory are out of the scope of this thesis. Therefore, the delay time is also the difference between arrival time of the desired trajectory and arrival time of the alternative trajectory.

$$C_{TMD}^i(\delta t^i) = \delta t^i \cdot p_d \tag{4.15}$$

The fuel trajectory modification costs ($C_{TMF}^i(\delta h^i)$) as given in Equation 4.16 is the difference in fuel costs between flying the desired trajectory ($C_{F,des}^{i,t}$) and flying the alternative trajectory ($C_F^{i,t}(\delta h^i)$) over each waypoint within the set of timestamps T^i for the trajectory i. Fuel costs of a trajectory are calculated by multiplying fuel price with fuel consumption.

The fuel price (p_f) is the yearly average jet fuel price handled by the International Air Transport Association (IATA) [46] [40]. The fuel consumption (c_f) is calculated using BADA, an APM developed and maintained by EUROCONTROL. The inputs to obtain the fuel consumption of a trajectory are the 4D coordinates, the aircraft type, the flight phase (climb, descent, cruise) and the aircraft mass level (low, nominal, high). The aircraft total mass and airspeed are assumed to be nominal. According to [47] BADA currently covers only 70% of current aircraft types operating in European airspace.

In case an aircraft type is not recognised by BADA, the APM of Europe's most operating aircraft [40], the Airbus A320, is used.

$$C^i_{TMF}(\delta h^i) = \sum_{t \epsilon T^i} \left(C^{i,t}_{F,des} - C^{i,t}_F(\delta h^i) \right) \tag{4.16}$$

$\Phi_{tot}(\delta h, \delta t)$ in Equation 4.11 is the total amount of interacting trajectories, as given in Equation 4.17, which is multiplied by the constant M. This constant has a value of at least a higher order of magnitude than the largest possible trajectory modification costs in the network. In this way, the algorithm will always prioritise reduction in TIs over reducing fuel and delay trajectory modification costs. The equation is similar to Equation 4.7 used for initial TID.

$$\Phi_{tot}(\delta h, \delta t) = \sum_{i \epsilon I} \Phi^i(\delta h^i, \delta t^i) \quad \forall t \in T \tag{4.17}$$

As previously explained in Subsection 4.3 and given in Equation 4.18, Φ^i has a binary value as it indicates whether a trajectory i interacts ($\Phi^i = 1$), or does not interact ($\Phi^i = 0$) with another trajectory. An interaction occurs when the minimum allowed horizontal separation distance N_H, and/or the minimum allowed vertical separation distance N_V between two trajectories is infringed. The distance calculations between two trajectories on horizontal and vertical level are given in Equations 4.19 and 4.20, respectively.

$$\Phi^i(\delta h^i, \delta t^i) = \begin{cases} 0 & \text{if} \quad d^{i,j}_H(\delta t^i) \geqslant N_H \vee d^{i,j}_V(\delta h^i, \delta t^i) \geqslant N_V \quad \forall j \in J, i \neq j \\ 1 & \text{if} \quad d^{i,j}_H(\delta t^i) < N_H \vee d^{i,j}_V(\delta h^i, \delta t^i) < N_V \quad \forall j \in J, i \neq j \end{cases} \tag{4.18}$$

$$d^{i,j}_H(\delta t^i) = \sqrt{(x^i(\delta t^i) - x^j)^2 + (y^i(\delta t^i) - y^j)^2} \tag{4.19}$$

$$d^{i,j}_V(\delta h^i, \delta t^i) = h^i(\delta h^i, \delta t^i) - h^j \tag{4.20}$$

Equation 4.12 is the allowed departure time shift constraint. As it is not reasonable to delay the departure time of a flight for too long, the departure time shift δt^i will be limited to lie in the interval $\Delta t^i = [0, \delta t^i_{max}]$. δt^i_{max} is the maximum allowed departure time shift of each flight i with $\delta t^i_{max} > 0$. Given a time shift step size δ_{ds} (set by the user), this corresponds to the possible delay slots of flight i being $n^i_d = \delta t^i_{max} / \delta_{ds}$. Therefore, the set of all possible delays is given by $\{0, \delta_{ds}, ..., (n^i_d - 1)\delta_{ds}, n^i_d \delta_{ds}\}$.

Equation 4.13 is the allowed FL change constraint. As it is not reasonable to change the height of a flight by too much, the FL change δh^i will be limited to lie in the interval $\Delta h^i = [0, \delta h^i_{max}]$. δh^i_{max} is the maximum allowed FL change of each flight i with $\delta h^i_{max} < 0$. Given a FL change step size δ_{hs} (set by the user), this corresponds to the possible height levels of flight i being $n^i_h = \delta h^i_{max} / \delta_{hs}$. Therefore, the set of all possible heights is given by $\{0, \delta_{hs}, ..., (n^i_h - 1)\delta_{hs}, n^i_h \delta_{hs}\}$.

4.4.2. Genetic algorithm

The mathematical program described in Subsection 4.4.1 is solved using a GA, a search heuristic inspired by the Darwinian evolutionary theory of natural selection, the process that drives biological evolution. In this algorithm the fittest individuals are selected for reproduction to produce offspring of the next generation.

The general process of the GA is shown in Figure 4.6. In the first phase, an initial population is created, followed by calculation of the fitness function. Subsequently, the fittest individuals are selected. Afterwards, the crossover and mutation phases take place. This process repeats until the population has converged and the generation with the fittest individuals are found. The different phases are explained in detail below.

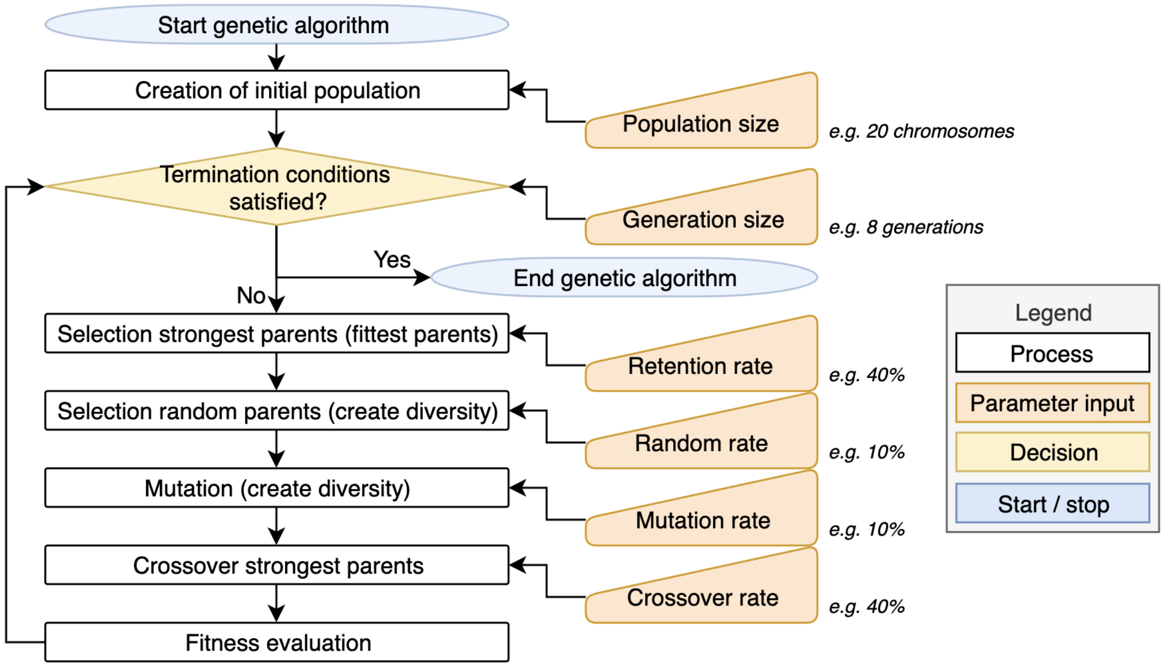


Figure 4.6: Genetic algorithm process.

In a GA, the population is evolving into better solutions every generation until convergence is reached. As shown in Figure 4.7 a population consists of a set of individuals, called chromosomes. Each chromosome represents a solution for the network optimisation problem to be solved. Each chromosome consists of a set of genes, which in this case are the individual trajectories within the network. Each gene has two decision variables, departure delay and FL decrease. These parameters represent the TIR strategies.

Initial population

The process to form the initial population is shown in Figure 4.8. Before the random decision variables δt^i and δh^i are assigned to the trajectories, the original desired trajectories are assigned to certain clusters. These clusters are formed to reduce computation time during the computationally exhaustive crossover step. Tests were conducted to perform crossover without clustering of chromosomes but no results could be generated within limited amount of time.

As indicated in Figure 4.9, the clusters are formed by grouping all trajectories which will potentially interact with each other within decision variable range (for each value of δt^i and δh^i). For example, it is possible that two trajectories 1 and 3 would not interact with each other if trajectory 1 has a departure delay of $60s$ and FL decrease of $300m$, and trajectory 2 has a departure delay of $0s$ and FL decrease of $0m$. However, they would interact with each other with different decision variables for departure delay and FL decrease. Therefore, both aircraft are grouped into one cluster. The entire range of decision variables is taken into account.

After clusters have been detected and stored, different chromosomes (network solutions) are formed with genes (alternative trajectories) of randomly assigned delay δt^i and FL decrease δh^i, together forming one population. The initial population is called the first generation.

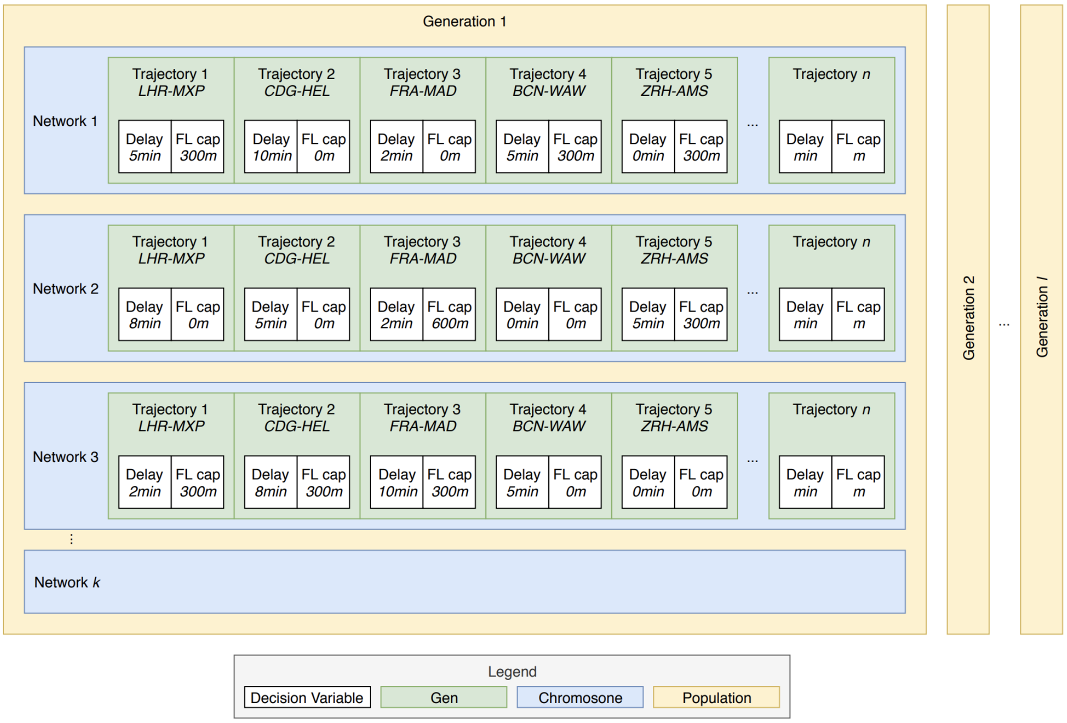


Figure 4.7: Genetic algorithm terminology.

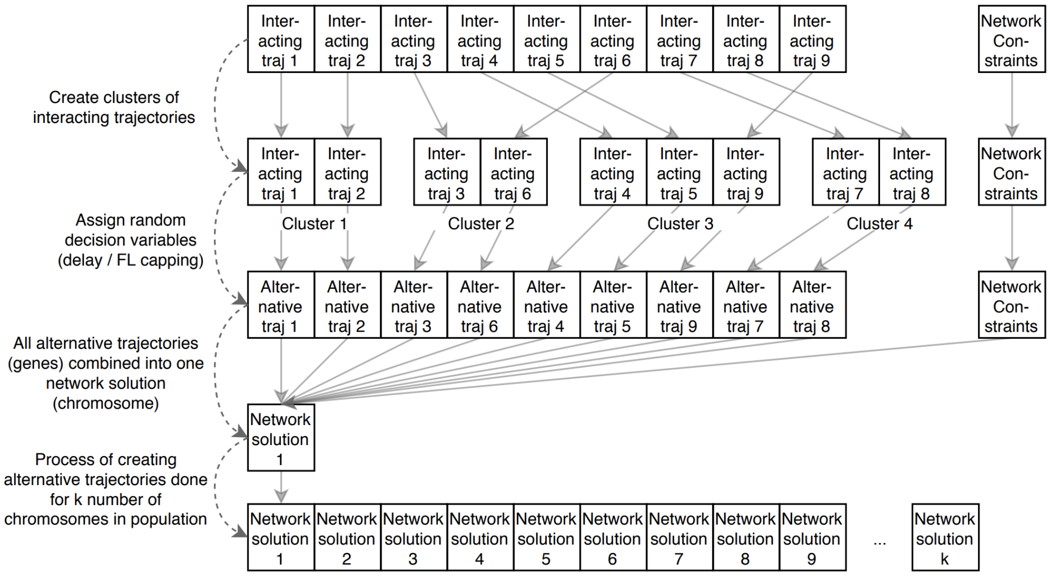


Figure 4.8: Initial population creation process.

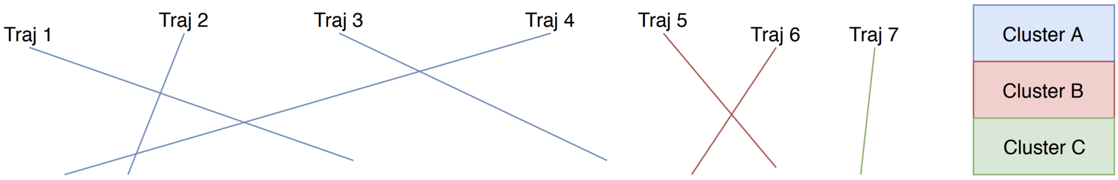


Figure 4.9: Example of clusters.

Fitness function

After creation of the initial population, the next step in the process is to evaluate the fitness function of each network solution (chromosome) in the population, as seen in Figure 4.10. A fitness score is given to each individual. The probability that an individual will be selected for reproduction is based on its fitness score. During each generation, the GA resolves TIs by searching for alternative trajectories maximising the fitness function. The fitness function F provided in Equation 4.21 corresponds to objective function 4.11. Constraints 4.12 and 4.13 given in the mathematical model define the range of the decision variables.

$$F = C_{TM} + \Phi_{tot} \cdot M \tag{4.21}$$

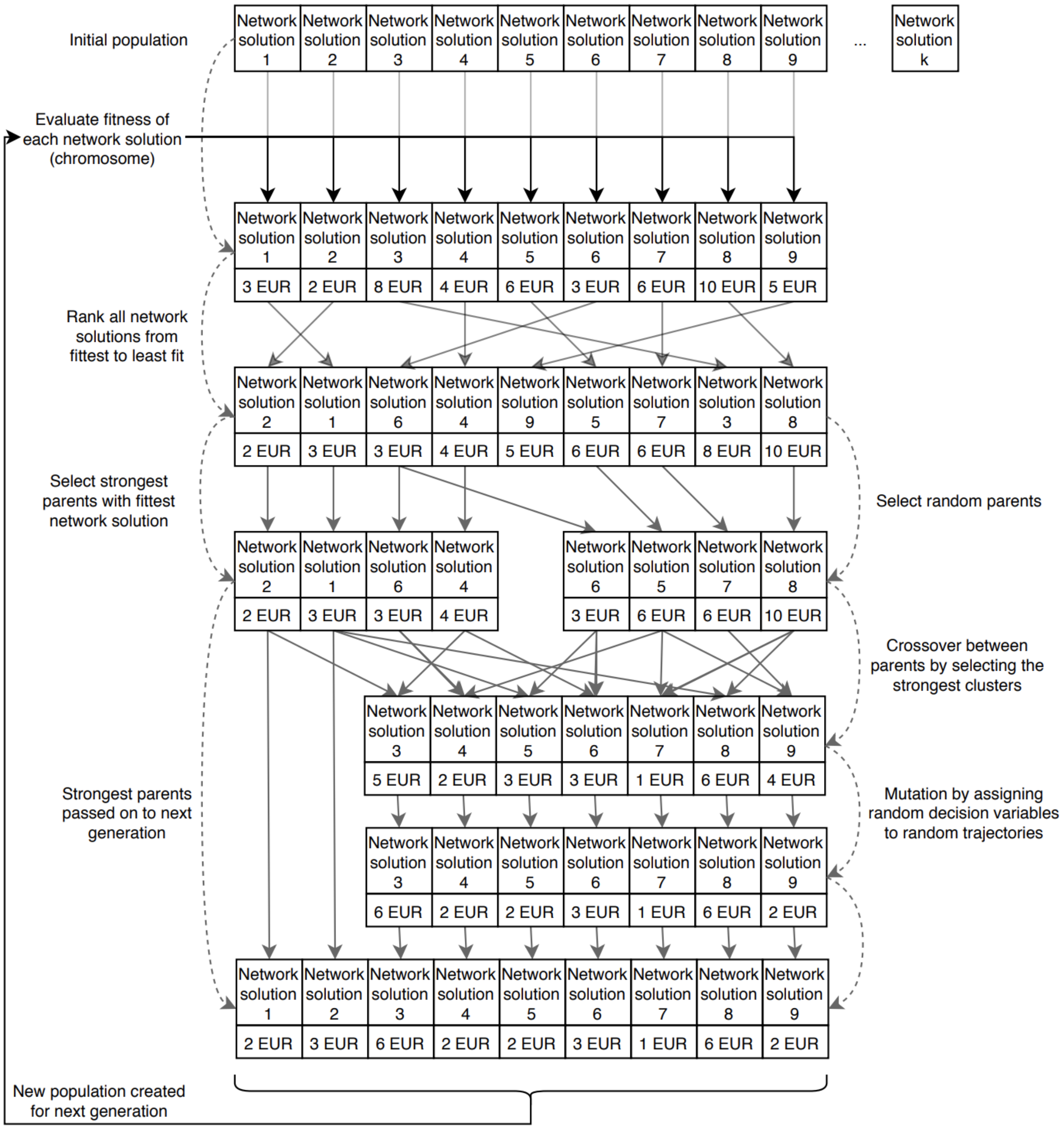


Figure 4.10: Genetic algorithm applied on the network-wide trajectory planning problem.

Selection

After calculation of the fitness of each network solution, the chromosomes are ranked from fittest to least fit as shown in Figure 4.10. The chromosomes with the best fitness score are selected, and its genes are passed on to the next generation. The amount of network solutions passed on to the next generation depends on the retention rate. This parameter could be changed. Furthermore, diversity is necessary to not get stuck on convergence to a local optimum and to allow exploration of the fitness landscape [48]. In order to do so, some random network solutions are selected as well. The amount of network solutions selected randomly depends on the random rate. This parameter could also be changed.

Mutation

After selection of both strongest and random network solutions, mutation is introduced. Similar to randomness, mutation is an important characteristic to increase diversity [48]. Mutation is introduced by assigning random decision variables to random trajectories within a network solution.

Crossover

After the mutation phase, crossover takes place to generate new offspring. As discussed earlier in this Section, due to computational limitations clusters had to be generated and used for crossover. Figure 4.11 depicts an example of crossover between different selected network solutions. A multi-parent approach was used, as this results in better performance compared to a two-parent approach in terms of convergence [49].

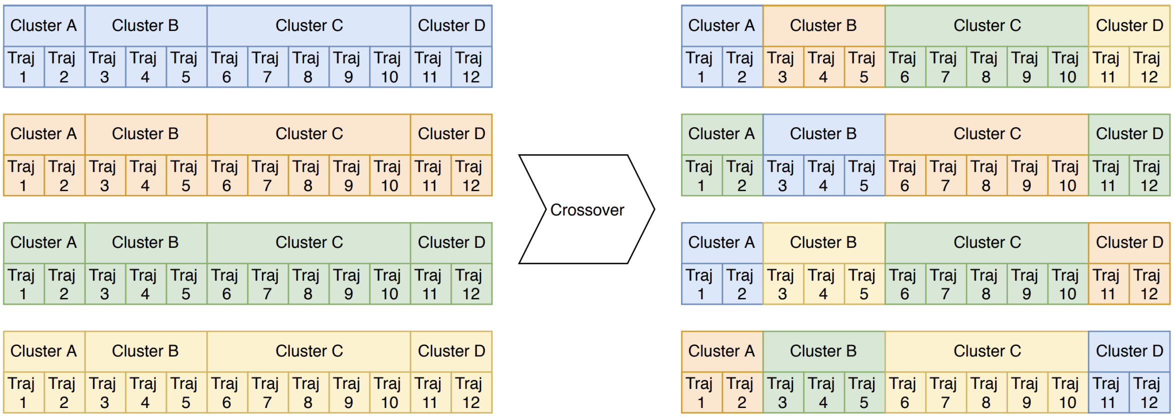


Figure 4.11: Example of crossover between parents.

Termination

The termination condition of the GA is important to end the process after convergence. Usually, a GA progresses fast in the initial phase, but saturates in later stages where improvements tend to be smaller. A termination condition makes sure the GA stops when the solution is close to the optimal.

According to [50] two main termination approaches could be used. First, after reaching an absolute number of iterations. Second, when no improvement has occurred for a specified amount of iterations. The latter approach is not within the scope of the thesis as for this, multiple test have to be conducted and parameters should be optimised. Therefore, the former approach will be used.

5

Case Study

The goal of the case study is to test the proposed network-wide trajectory planning algorithm on real traffic data, to see whether it is capable of detecting and resolving trajectory interactions. Additionally, to see what the limitations of the algorithm are which could be tackled in future work.

This chapter entails as follows. First the experimental setup is provided with an elaboration on the used equipment, software, and input data. Second the scope in terms of airspace range and time is provided. Finally, the parametric values are given.

5.1. Experimental setup

This section contains details on the hardware equipment, software language, and type of data used for the simulations. Figure 5.1 depicts the setup, which is elaborated upon in the subsequent parts of this section.

5.1.1. Hardware

The simulations were performed on laptop with a $2.7GHz$ Intel Dual Core i7 processor and $16GB$ $1600MHz$ DDR3 RAM. This equipment is limited in terms of computational power compared to the equipment used in other literature. For example, in [27] a desktop computer with a $2GHz$ Quad core processor and $128GB$ RAM was used, and in [35] a desktop computer with a $3.9GHz$ Dual core processor and $32GB$ RAM was used.

5.1.2. Software

Optimisation algorithms and simulation visualisation tools for this specific research problem were built from scratch as no such programs exist or were accessible. All the algorithms were implemented in Python 3.6.3 (64-bit) as seen in Figure 5.1. This is a high-level, interpreted and general-purpose dynamic programming language that focuses on code readability. This popular language is developed under an open source license, and is supported by an open and mature community [51]. Therefore, it is a good choice with regards to potential future work built upon this project.

A relational database is used to store the large amounts of flat file data, extracted from the EUROCONTROL databases [52]. The relational database used for the project is PostgreSQL10. This database is also open source, and faster than its competitors [53].

The written code for this research problem is structured into different modules. The modularity allows to modify, add and remove features to the optimisation and simulation tool in future work.

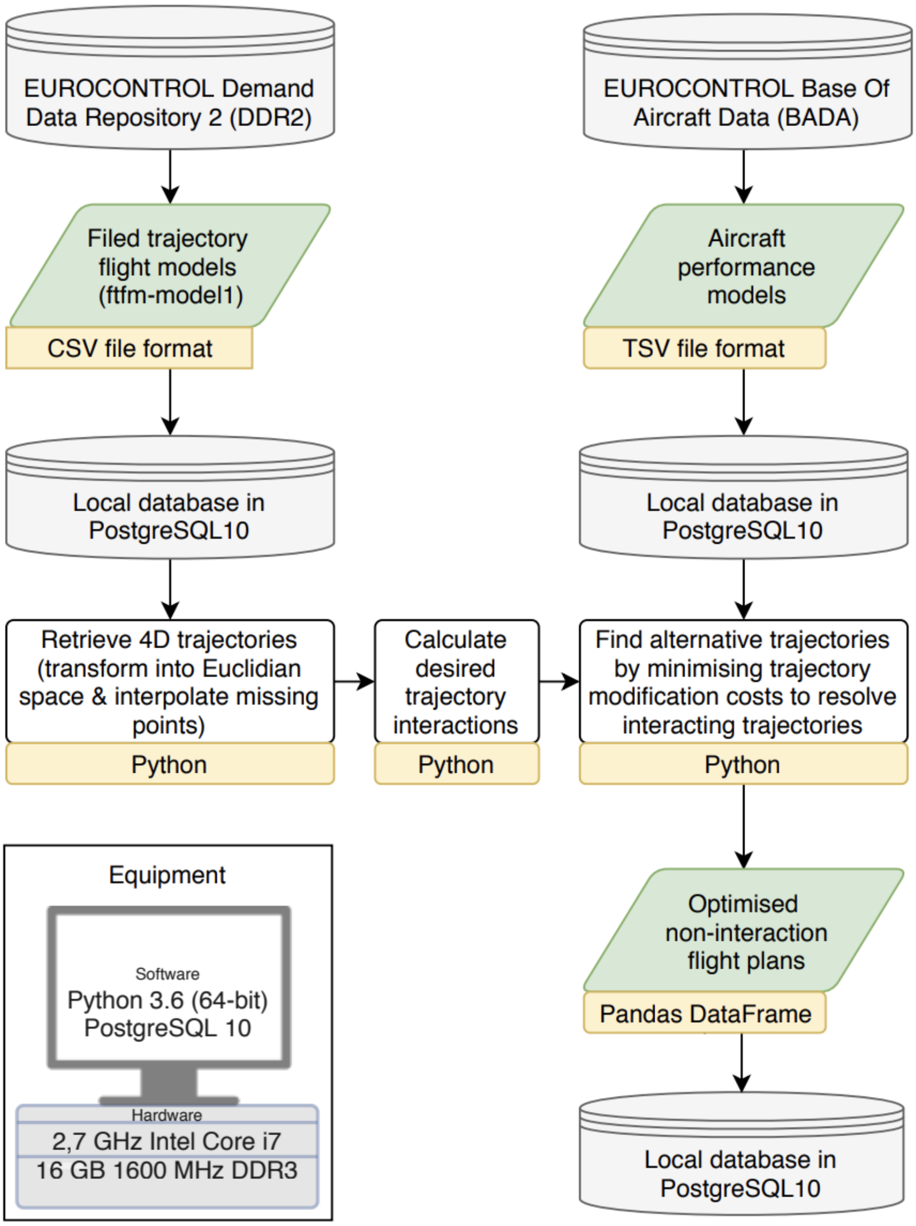


Figure 5.1: Experimental setup.

5.1.3. Input data

The goal of the thesis is to find a NWTP algorithm for future TBO environment. Therefore, forecasted future (e.g. year 2035) traffic data could be used which incorporates the expected increase in terms of number of flights. However, as this data is not available yet for Europe the scope of this thesis is limited to traffic data of one of the busiest days so far, namely 29 June 2018 for which 32955 FPLs were submitted.

The original FPL data was obtained from the EUROCONTROL Demand Data Repository 2 (DDR2) database. The original filed FPLs submitted by the airspace users, are called filed trajectory flight models (ftfm) often referred to as Model1-data. The data is extracted from the database in comma-separated values (CSV) file format.

The extracted data has been cleaned and processed before storing it into the PostgreSQL database. Duplicate FPLs with identical trajectories, and FPLs with missing coordinates at begin or end of the trajectory were discarded. As a result 19 flights corresponding to 0.06% of the original FPLs were filtered out.

Other data used as an input in the algorithms is EUROCONTROL BADA 4 data. More specifically, the aircraft performance models are used to calculate fuel consumption. The data is extracted from the database in tab-separated values (TSV) file format, and stored into the PostgreSQL database. In case an aircraft is not recognised in the BADA database, the model of Europe's most operating aircraft [40], the Airbus A320, is used. This is done for 12.2% of the filed FPLs. This significant number could be reduced by rerunning the simulations in the future with updated aircraft performance models in BADA4, as at the time the thesis is written only 70% of all aircraft flying above Europe are covered.

5.2. Scope

The trajectory scope is limited in time and space due to computational constraints. Therefore, a time range of one hour is considered. In future work, more computational power could be used to optimise a larger timeframe. In Figure 5.2 the amount of movements (arrivals and departures) and the amount of unique airborne flights per hour on 29 June 2018 is shown. The amount of unique airborne flights is a more relevant indicator for an en-route traffic optimisation problem. Therefore, the busiest hour for this indicator is selected. As encircled by red, the time range interval is $[15h, 16h]$. The airspace range considered for trajectory interaction detection and resolution is limited to the European airspace. Therefore, the latitude and longitude interval are $[30.0°, 80.0°]$ and $[-15.0°, 40.0°]$, respectively [1].

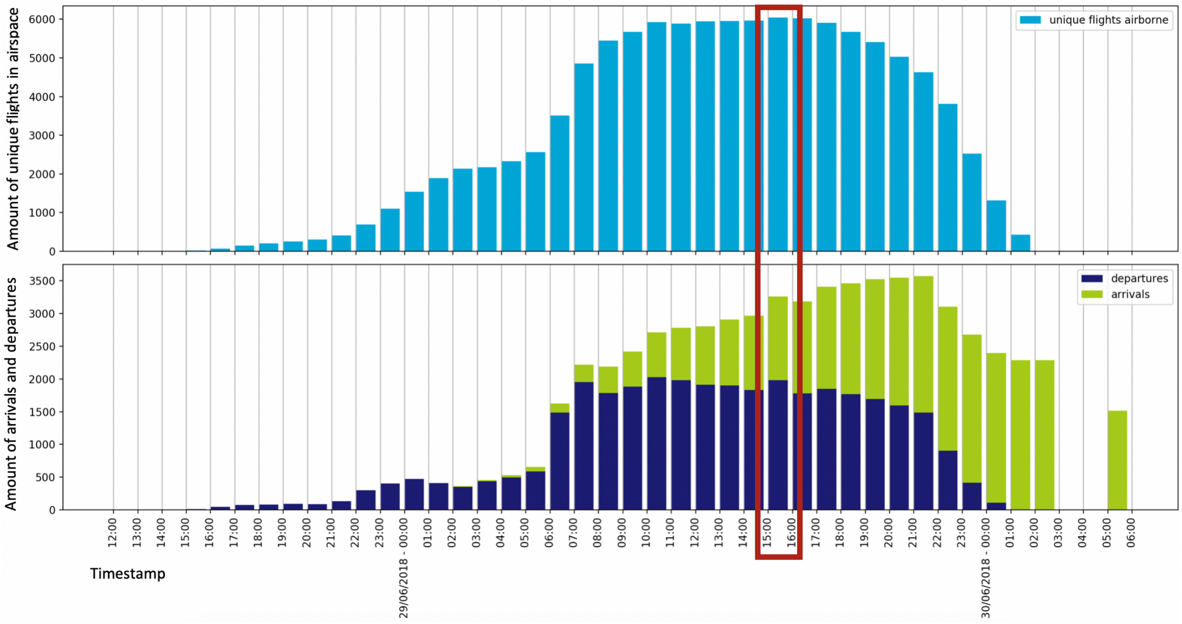


Figure 5.2: Amount of unique airborne flights and movements per hour in Europe on 29 June 2018.

Additionally, as explained in Section 4.2, flights which are within a $50NM$ radius around departure or arrival airport are not taken into account in this thesis. The amount of unique flights within scope considered for this case study is 4440 flights.

5.3. Parametric values

The cost parameters used to calculate TMC and TIC are given in Table 5.1. TMC is based on values used by EUROCONTROL as indicated in [40]. TIC is selected sufficiently large such that reduction in interactions are prioritised above reduction in modification costs as explained in Section 4.4. Furthermore, the decision variable constraints are provided. The genetic algorithm specific parameters are indicated in Table 5.2.

Table 5.1: Parametric values of costs and constraints.

Parameter name	Value
Delay cost	1.67€$/s$
Fuel cost	0.31€$/kg$
Interaction cost	999999€
Maximum departure delay	600s
Maximum FL decrease	600m

Table 5.2: Parametric values of genetic algorithm.

Parameter name	Value
Population size	20 chromosomes
Generation size	25 generations
Retention rate	20%
Random rate	20%
Mutation rate	20%
Crossover rate	40%

6

Results

In this chapter, first the results of the trajectory interaction detection mechanism are given in Section 6.1. Subsequently, the trajectory interaction resolution mechanism results are described in Section 6.2. These mechanisms are applied on the case study described in Chapter 5.

6.1. Trajectory interaction detection

This section entails the results and evaluation of the TID-process using the grid-based method explained in Section 4.3. The goal of the TID is to detect all trajectory interactions on a network-wide level. The input is a set of trajectories based on the filed FPLs as explained in Section 4.2. The output is a set of non-interacting trajectories, and a set of interacting trajectories.

Table 6.1 indicates some key figures on the TID process applied on the case study described in Chapter 5. Out of the 4440 total flights considered within scope, a total of 2364 interacting trajectories were detected. The average runtime to detect the interactions is 121.9s covering one hour of traffic above Europe. Furthermore, 13.57% of all occupied cells within the network are occupied by more than one aircraft, for which the distance between the occupying waypoints is calculated. The occupied cells represent on average 0.04% of the total amount of cells within the entire volume.

Table 6.1: Grid cell occupancy results.

	Total within scope	**Average per timestamp**
Amount of total 3D cells within volume	1081080000	6006000
Amount of flights	4440	2644
Amount of waypoints per flight	105	105
Amount of occupied cells	409953	2278
Amount of occupied cells by more than one flight	55620	309
Amount of occupied cells + neighbouring cells	11068724	61493
Amount of interacting trajectories	2364	82
Interacting trajectories / all flights within scope	53.24%	3.10%
Occupied cells by more than one aircraft / all occupied cells	13.57%	13.57%
All occupied cells / all cells within volume	0.04%	0.04%
All occupied cells + neighbouring cells / all cells within volume	1.02%	1.02%

To check whether the detection mechanism is able to detect TIs, the visual given in Figure 6.1 is built. Top left shows the map within scope in 2D (longitude vs latitude). Bottom left and top middle indicate the height of the trajectory. Top right provides more details on the TIs and their grid cells. Bottom middle provides more information on the grid-based method. The middle column presents the occupied cells within the grid for 1 flight, 2 flights, 3 flights and more than 3 flights detected in one cell. The number not between brackets indicates the occupied cells with their neighbouring cells included. The number between brackets indicates the occupied cells without neighbouring cells considered. The cells occupied by more than one flight are subsequently checked on the actual distance between the waypoints. If the minimum separation is infringed at least once along the trajectory, an actual interaction exists. The interactions, occupied cells, and amount of flights in the network are plotted over time in the graph at the bottom right of the picture.

6.2. Trajectory interaction resolution

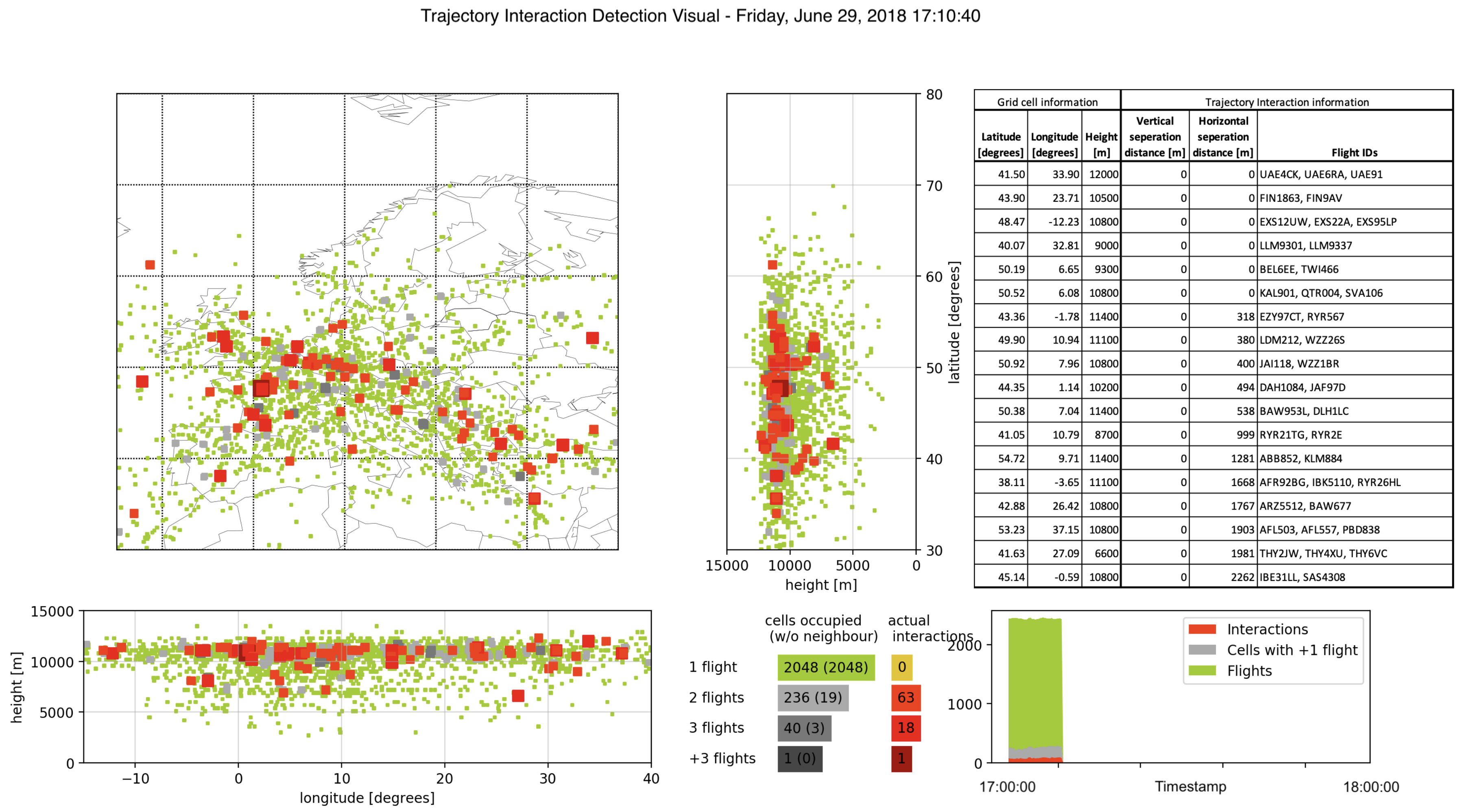
After the trajectory interaction detection process, the trajectory interactions are resolved using a genetic algorithm. Optimisation of genetic algorithm parametric values is out of the scope of this thesis. The parametric values used in this thesis are given in Table 5.2.

The network efficiency indicators and network stability indicators are shown in Figure 6.2. The top graph indicates the total costs per generation, consisting of both trajectory modification costs (fuel costs, caused by FL decrease and departure delay costs, caused by delay) and trajectory interaction costs. The middle graph represents the trajectory modification costs per generation. The bottom graph represents the decision variables (departure delay and FL decrease), and amount of interactions per generation.

As seen in Figure 6.2, the amount of total costs decreases every generation. However, after 17 generations the decrease stagnates at 498 interactions (79% of initial interactions resolved). In order to solve this issue, the genetic algorithm parameters could be optimised. Additionally, the decision variable limitations could be changed to allow for more delay per flight and FL decrease. The optimisation process for 25 generations on a network wide level takes $23h\ 29min\ 2s$. This is slow for only one hour of traffic, as balancing mechanisms for current ATM environment such as the CASA optimise the network in seconds [54]. One has to note however, that current balancing is done on macroscopic level (demand-capacity balancing), while the proposed algorithm balances on microscopic level (trajectory optimisation within network). The middle graph indicates that the biggest share of TMC are departure delay costs.

The individual efficiency indicators (average FL decrease per flight and average departure delay per flight) and individual stability indicators (maximum FL decrease per flight and maximum departure delay per flight) are given in Figure 6.3. One could see that both the average FL decrease and departure delay, increase over time. However, this data does not indicate whether the algorithm minimises departure delay costs and FL decrease costs after the interactions are resolved.

In order to look deeper into this, tests are conducted on a smaller area shown in Figure A.2 which ranges from $[48.0°, 52.0°]$ longitude and $[-2.0°, 2.0°]$ latitude. Furthermore, the amount of generations is extended to 100. A total of 121 interactions are detected in the smaller area between $15h$ and $16h$. Figure 6.4 depicts the cluster size vs. occurrence. 61 interactions or about 50% of the total amount of interactions are clustered within a cluster of 2 or 3 aircraft. Furthermore, Figure 6.5 shows that the runtime per generation lowers over time. The reason for this is the memory characteristic of the algorithm. More specifically, if a certain result (TMC) of a decision variable combination within a cluster (departure delay and FL decrease for each aircraft within the cluster) has been found, the result is stored into a temporary table. If the same decision variable combination is used again in a different generation, the result is pulled out of the temporary table instead of being calculated again.



Grid cell information			Trajectory Interaction information		
Latitude [degrees]	**Longitude [degrees]**	**Height [m]**	**Vertical seperation distance [m]**	**Horizontal seperation distance [m]**	**Flight IDs**
41.50	33.90	12000	0	0	UAE4CK, UAE6RA, UAE91
43.90	23.71	10500	0	0	FIN1863, FIN9AV
48.47	-12.23	10800	0	0	EXS12UW, EXS22A, EXS95LP
40.07	32.81	9000	0	0	LLM9301, LLM9337
50.19	6.65	9300	0	0	BEL6EE, TWI466
50.52	6.08	10800	0	0	KAL901, QTR004, SVA106
43.36	-1.78	11400	0	318	EZY97CT, RYR567
49.90	10.94	11100	0	380	LDM212, WZZ26S
50.92	7.96	10800	0	400	JAI118, WZZ1BR
44.35	1.14	10200	0	494	DAH1084, JAF97D
50.38	7.04	11400	0	538	BAW953L, DLH1LC
41.05	10.79	8700	0	999	RYR21TG, RYR2E
54.72	9.71	11400	0	1281	ABB852, KLM884
38.11	-3.65	11100	0	1668	AFR92BG, IBK5110, RYR26HL
42.88	26.42	10800	0	1767	ARZ5512, BAW677
53.23	37.15	10800	0	1903	AFL503, AFL557, PBD838
41.63	27.09	6600	0	1981	THY2JW, THY4XU, THY6VC
45.14	-0.59	10800	0	2262	IBE31LL, SAS4308

Figure 6.1: Base case: network-wide trajectory interaction detection visual.

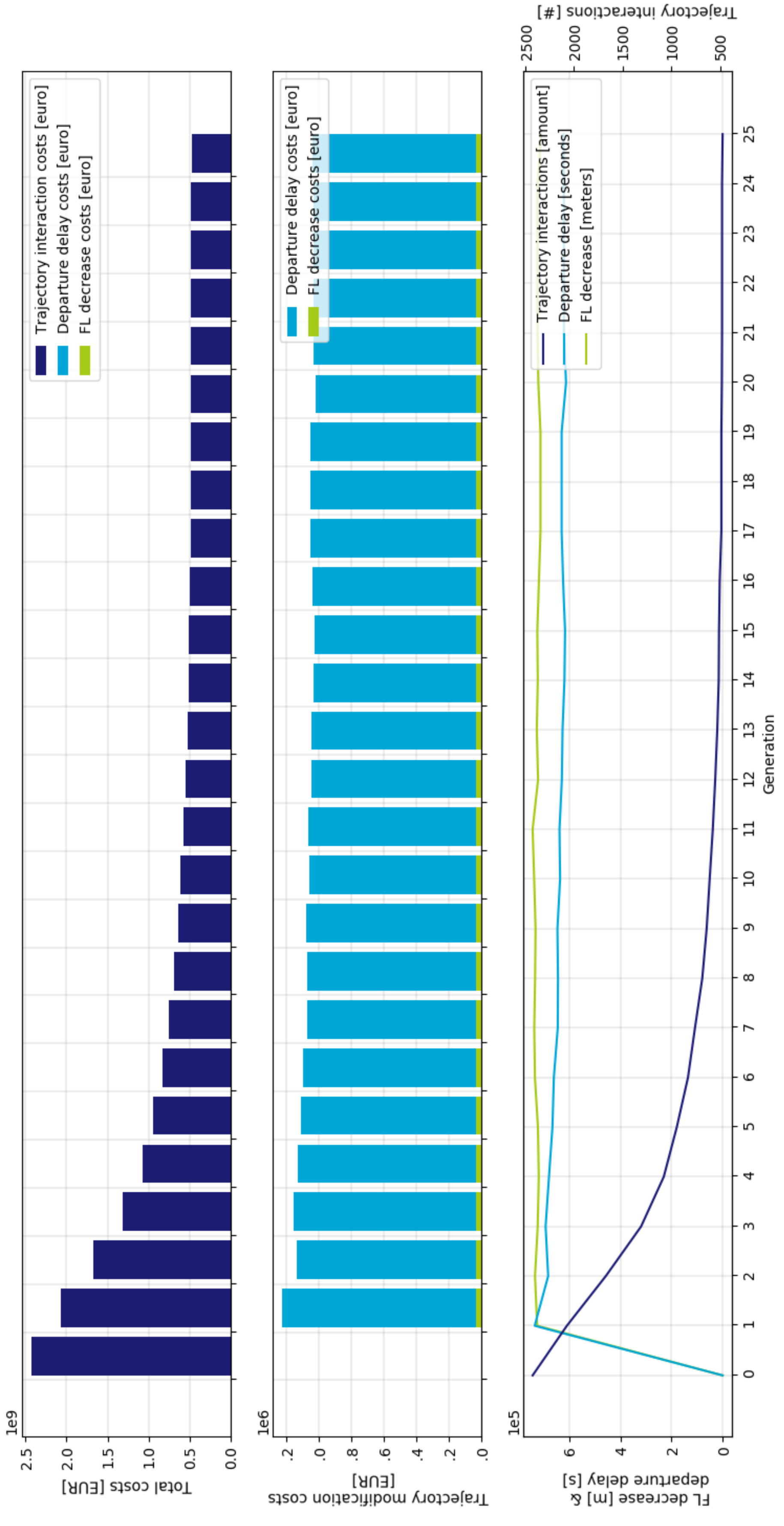


Figure 6.2: Base case: network efficiency and stability indicators.

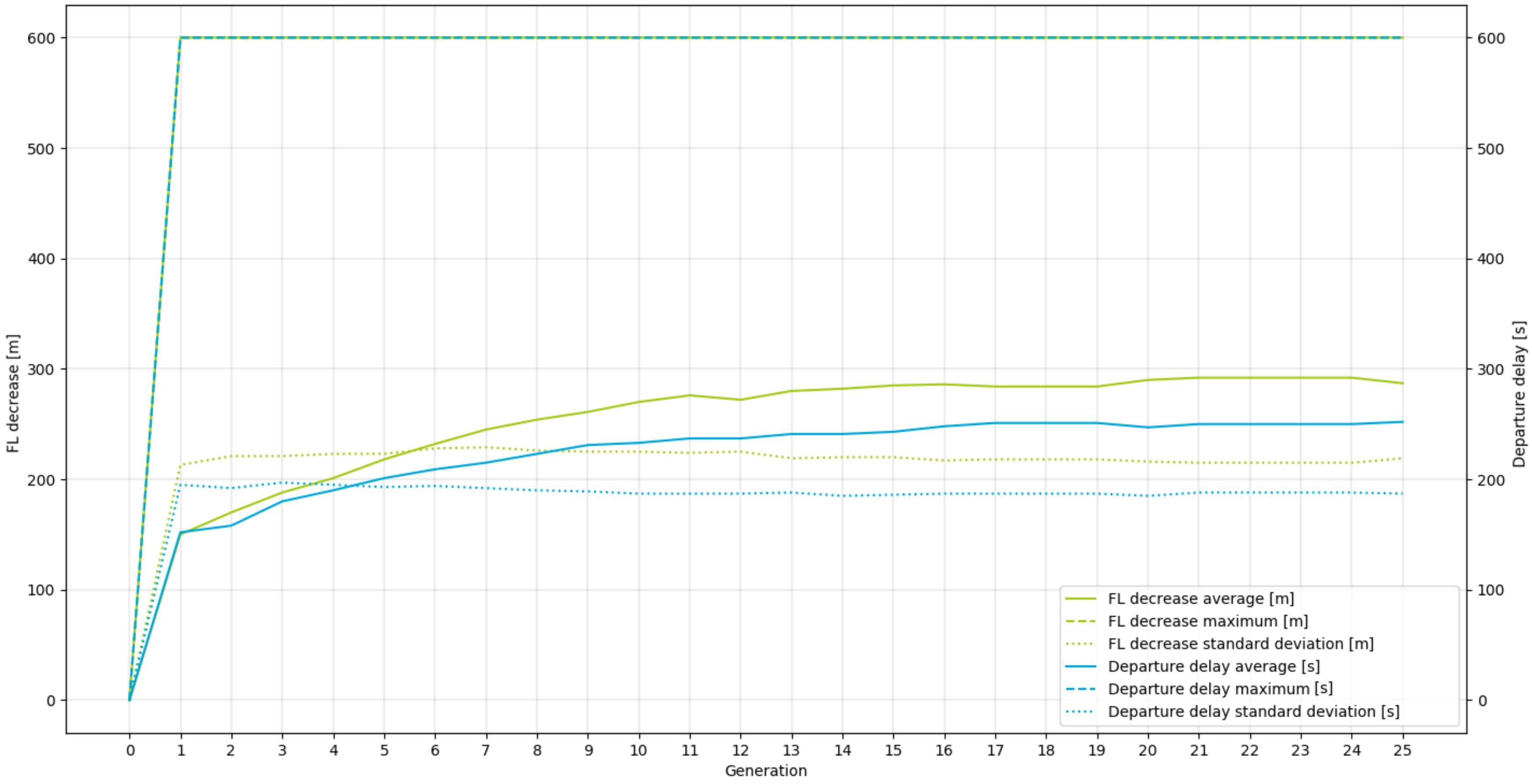


Figure 6.3: Base case: individual flight efficiency and stability indicators.

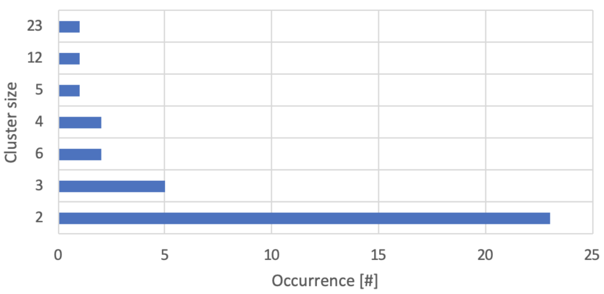


Figure 6.4: Small area case: cluster size distribution.

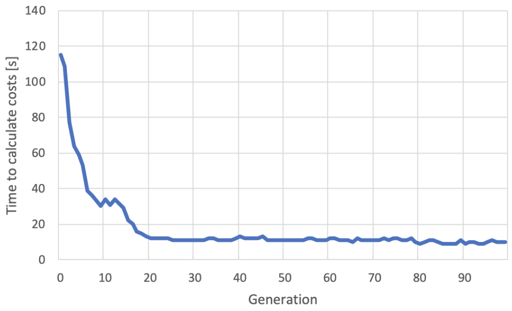


Figure 6.5: Small area case: runtime per generation.

Figure 6.6 indicates the change of decision variable combinations per generation. One could notice a mix of decision variable combinations in the first 10 generations, after which the combinations with smaller TMC (e.g. $300m$ FL decrease and $0s$ departure delay) increase over time, while the decision variable combinations with higher TMC decrease over time. Figure 6.7 and 6.8 indicate the departure delay distribution and FL decrease distribution of the last generation, where the skew towards the smaller decision variables with lower TMC is clearly visible.

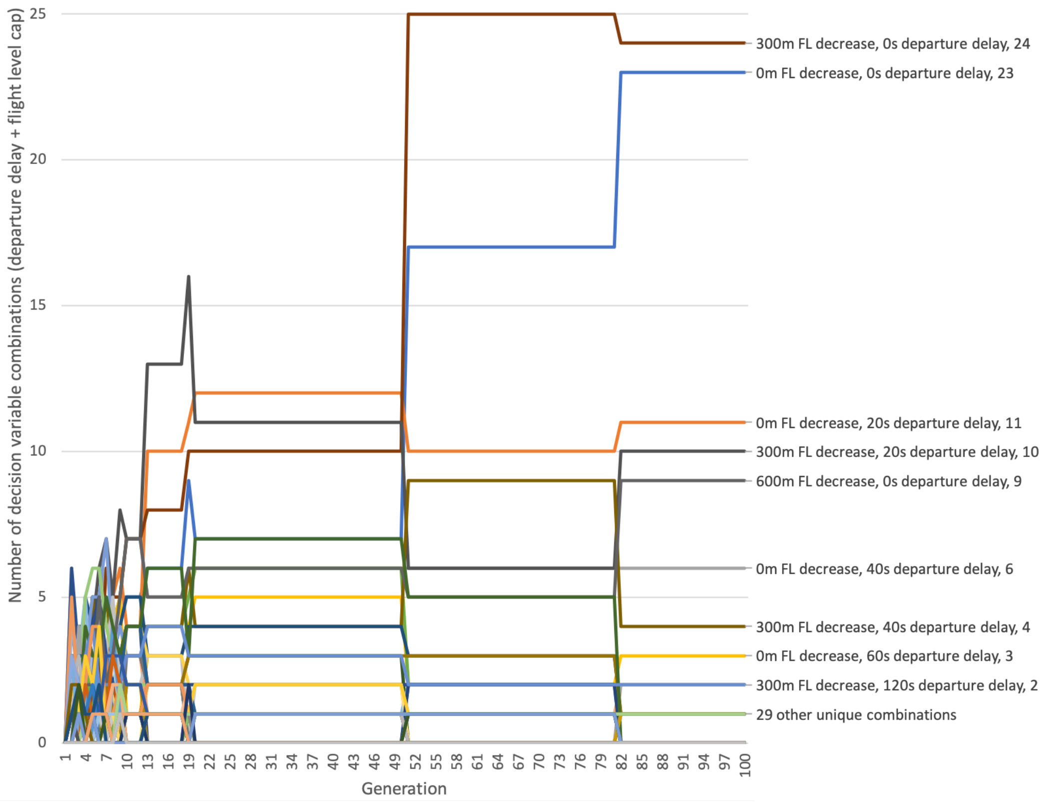


Figure 6.6: Small area case: decision variable evolution per generation.

The network efficiency and stability indicators of the algorithm applied on the smaller area are shown in Figure 6.9. Furthermore, individual efficiency and stability indicators are given in Figure 6.10. One could notice that due to the large penalty assigned to trajectory interactions within the trajectory modification costs fitness function (Equation 4.21), first the trajectory interactions

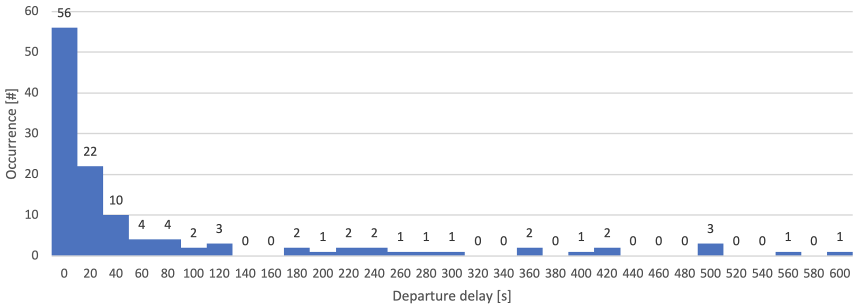


Figure 6.7: Small area case: departure delay distribution of generation 100.

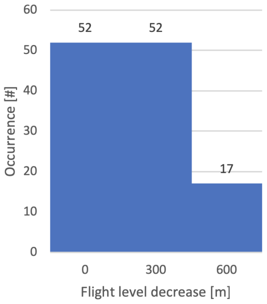


Figure 6.8: Small area case: flight level decrease distribution of generation 100.

are resolved. This sometimes leads to an increase in departure delay costs or FL decrease costs. An example of this could be seen at generation 20 of Figure 6.10. Subsequently, as soon as all interactions are resolved the algorithm minimises the trajectory modification costs. Examples are given at generation 50 and 81.

6.3. Sensitivity analysis

This section entails a sensitivity analysis on the cost parameters. The delay cost is changed from 1.67€/s to 0.167€/s. As seen in Figures 6.11 and 6.12, this results in a lower trajectory modification cost compared to the base case in Figures 6.2 and 6.3. Furthermore, one could notice the ratio departure delay costs over FL decrease costs decreases.

The amount of interactions resolved within 25 generations is not affected by a change in departure delay costs, as both cases go from 2346 to about 500 trajectory interactions within 25 generations and follow about the same amount of trajectory interaction resolutions per generation. One could conclude that changing the cost parameters will not result in resolving the interactions faster. In addition, the runtime to detect and resolve interactions did not change either.

In terms of individual flight stability indicators (maximum FL decrease per flight and maximum departure delay per flight), both remain capped by the maximum input values given as constraints (600m and 600s respectively).

The individual flight efficiency indicators change slightly, as the average FL decrease per flight is going down, and average departure delay per flight is going up. This is a result of the decreased delay cost, which results in departure delay being selected more often w.r.t. the base case.

6.4. Verification & validation

The type of verification and validation (V&V) that is being referred to in this section is the process of checking that the software system meets specifications and that it fulfils its intended purpose. With verification, one could check whether the product is built right. With validation, one could check whether the right product is built.

6.4.1. Verification

To verify the model, various processes and techniques are used to assure the model matches specifications and assumptions w.r.t. the model concept. The objective of model verification is to ensure that the implementation of the model is correct. The techniques used in this thesis are as follows.

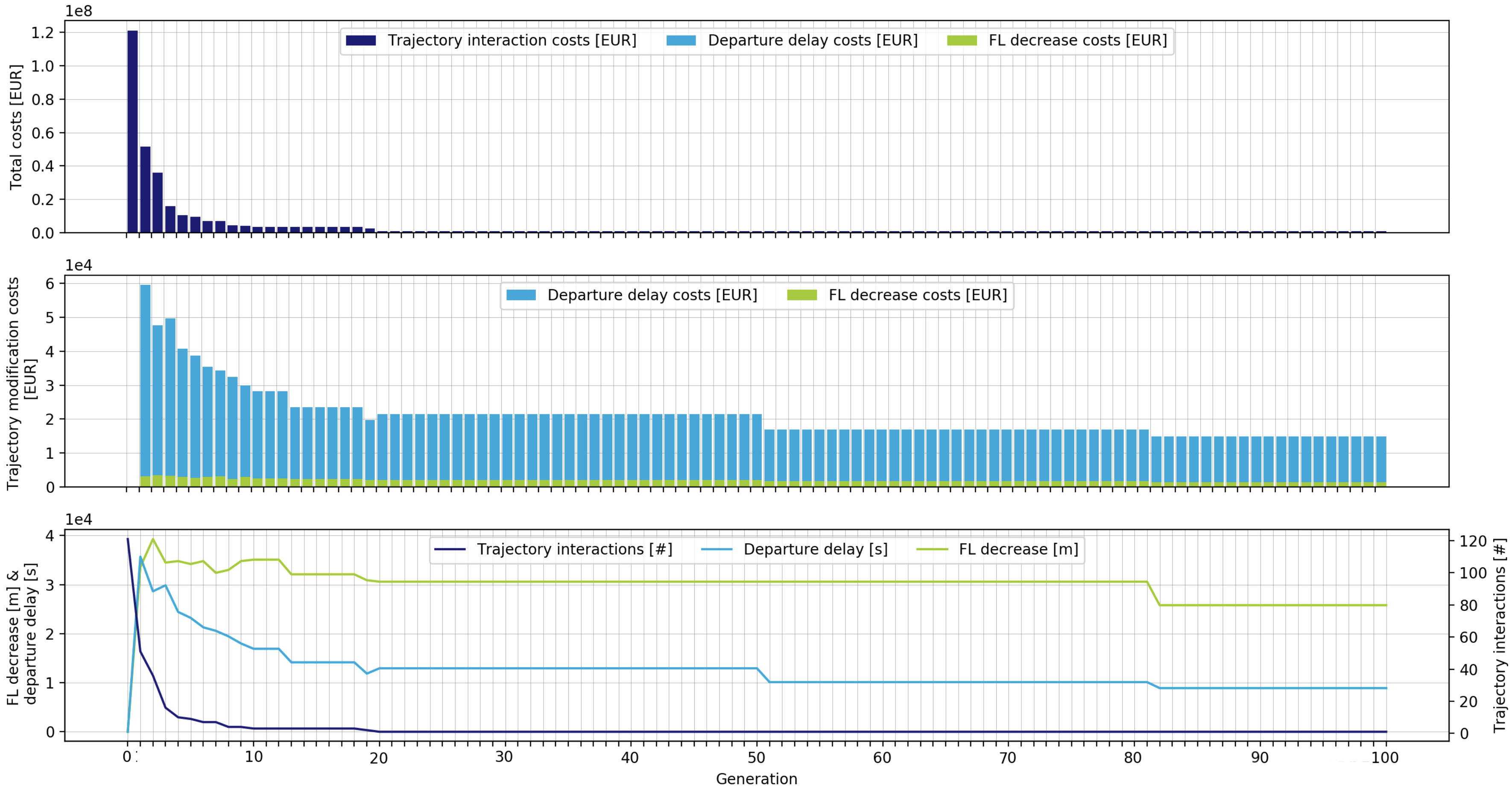


Figure 6.9: Small area case: network efficiency and stability indicators.

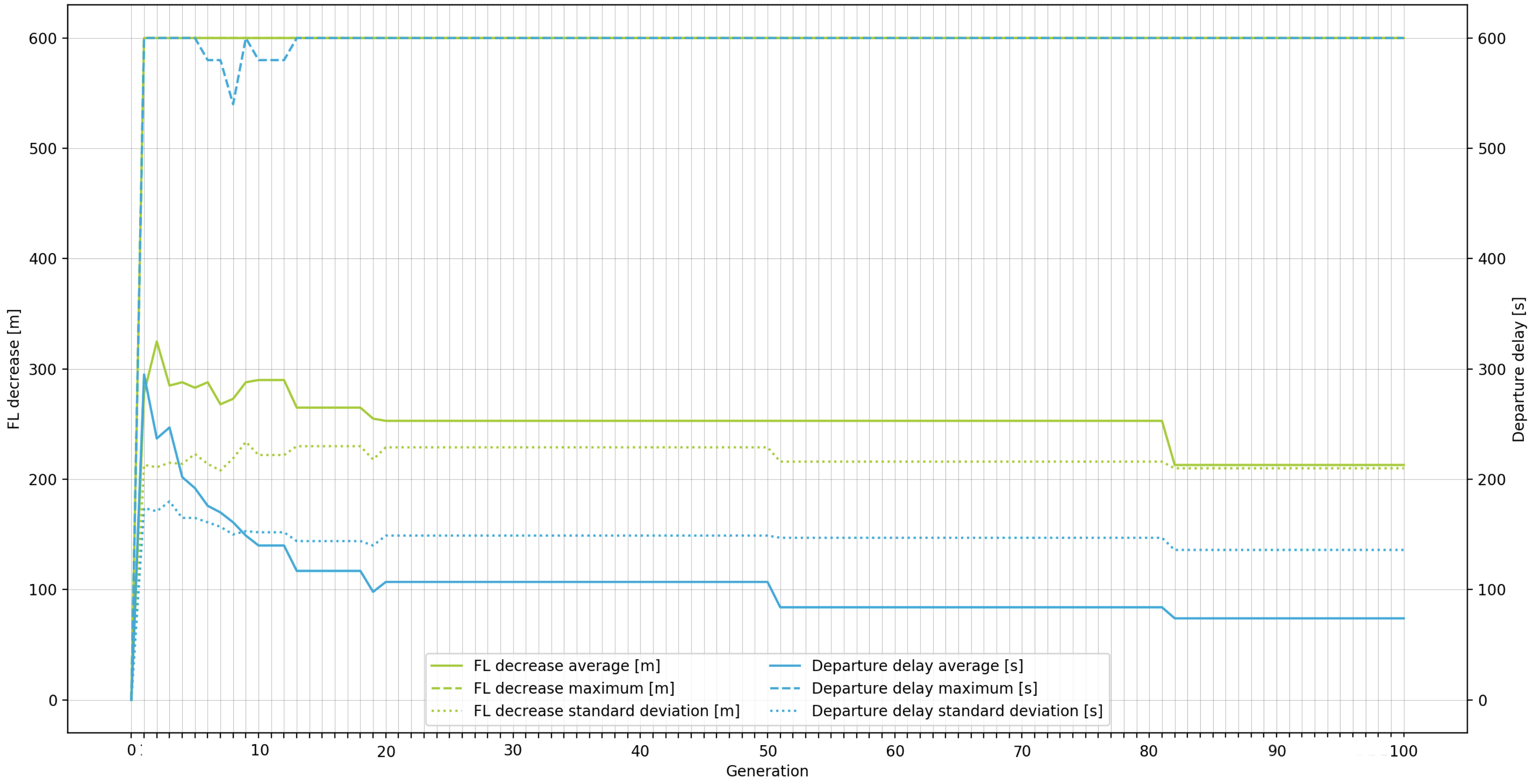


Figure 6.10: Small area case: individual flight efficiency and stability indicators.

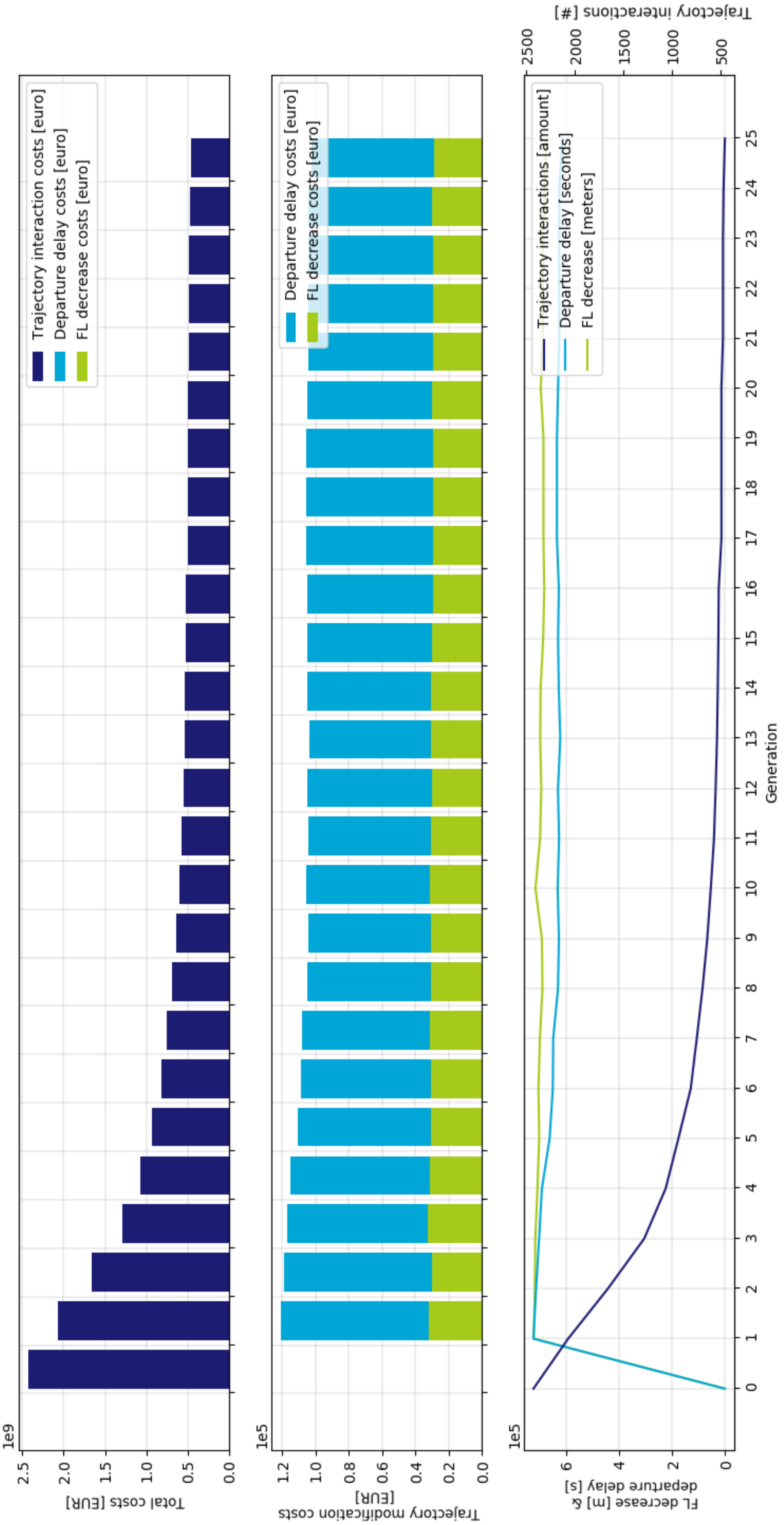


Figure 6.11: Base case - changed cost parameter: network efficiency and stability indicators.

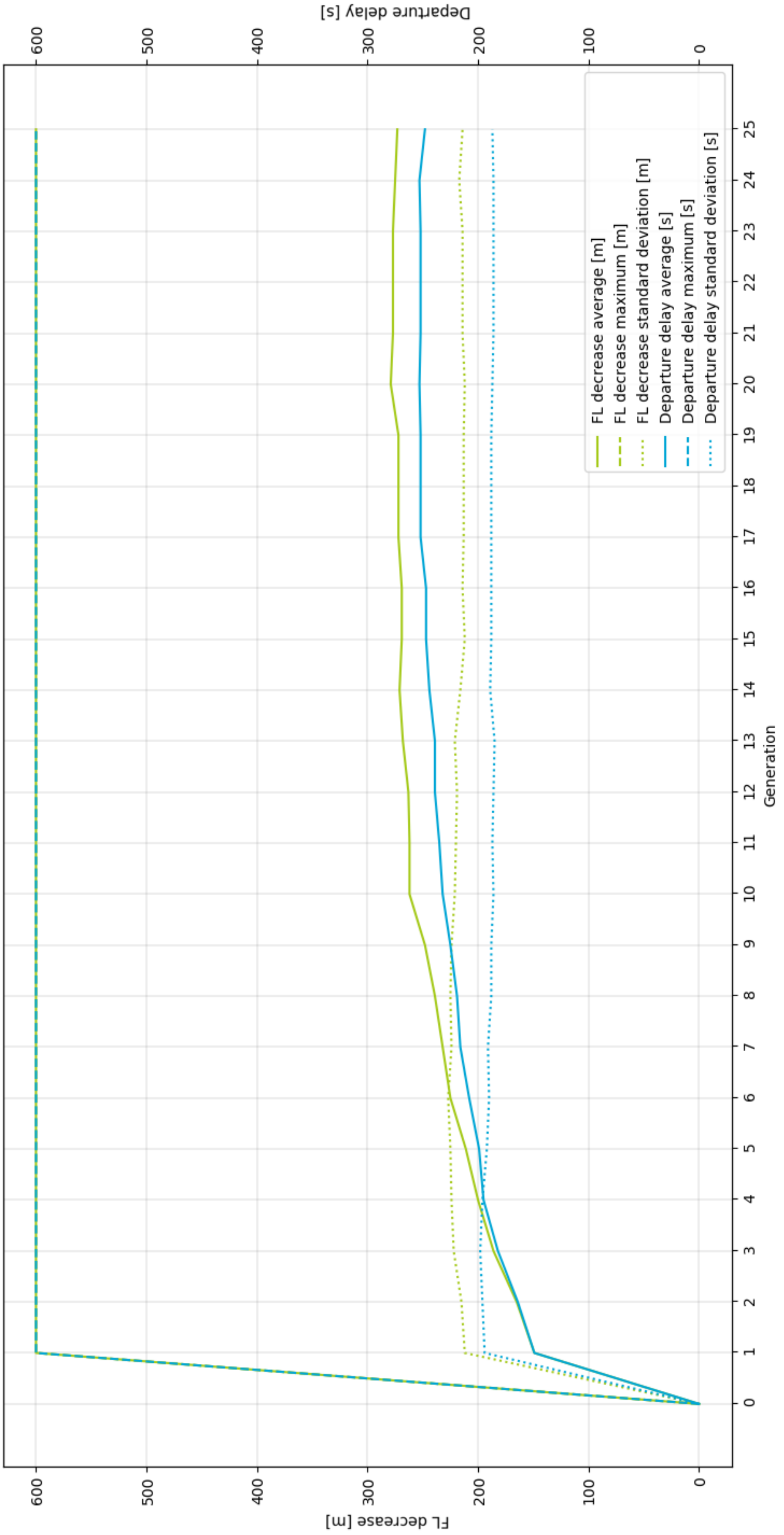


Figure 6.12: Base case - changed cost parameter: individual flight efficiency and stability indicators.

- *Antibugging*
  Antibugging is the process of including additional checks and outputs in a model that may be used to capture bugs if they exist. As programming is done in Python in this thesis, a large community is always available to help with any Python related questions.
- *Structured walk-through*
  The model was explained to other people in two type of groups in order to get other insights. This helps the writer to understand details of the model, and helps to become aware of bugs. The first group are the two supervisors continuously involved in the project. The second group are people not continuously involved in the project but with knowledge of either ATM or programming, such as one TU Delft professor, one TU Delft lecturer, two TU Delft thesis students, a EUROCONTROL engineer, and the ATMRPP Thirthy-fourth Working Group Meeting participants elaborated upon in the next subsection.
- *Tracing and animation*
  Tracing of outputs after each step in the algorithm is used to see what impact each step has, and to identify steps which are not working properly. Animation is similar but provides information about the internal behaviour of the model in a graphical form. For each of the three main processes as covered in Chapter 4 examples are given below.
  - Determination of 4D trajectories: During each subprocess such as adding flights/datapoints (interpolation) or removing datapoints (out of scope), a check has been performed which points were added/removed and whether the subprocess is executed completely. For example, the amount of datapoints for a trajectory could be calculated by dividing the time between arrival and departure by time step.
  - TID: a 4D visualisation is built to verify the process as shown in Figure 6.1. In this figure, one could notice it is hard to visually identify if an interaction is detected as soon as two flights pass too close to each other. Therefore, Figures A.1 - A.2 given in Appendix A, show a smaller area $[48.0°, 52.0°]$ longitude and $[-2.0°, 2.0°]$ latitude for two subsequent timestamps. Comparing the figures with each other, one could notice dots move each timestamp, and are indicated in red as soon as they interact.
  - TIR: During each generation, the new population is printed and checked to see which steps have taken place (e.g. selection of X, Y and Z individual), why (e.g. fittest parent), and what the differences are compared to the previous generation.

6.4.2. Validation

As no TBO environment or no open source simulators exist yet which are able to simulate NWTP in a TBO environment, it is difficult to validate the methodology and results of this thesis. Therefore, expert validation is used to validate the approach described in this thesis.

In order to validate the approach to see whether it meets the specifications, the methodology and preliminary results were proposed by means of Information Paper ATMRPP-WG/34-IP/06, and a presentation at the ICAO ATMRPP Thirty-fourth Working Group Meeting on the 25th of June 2018 at the Netherlands Aerospace Center in Amsterdam. This meeting, chaired by Mr. Henk Hof, was attended by 38 participants from twelve different ICAO member states and three international organisations.

This expert-group meeting was established by the ICAO Air Navigation Commission (ANC) in 2004 to work on ATM operational concepts including the development of the TBO Concept. The panel is expected to undertake studies to develop Standards and Recommended Practices (SARPs), procedures and guidance material necessary for evolutionary implementation of an integrated global ATM system.

In the Discussion Summary of the WG/34 meeting (ATMRPP-WG/34-SD), written by Ms. Crystal Guseul Kim, Technical Officer of the Aerospace Management and Optimisation Section of the ICAO Headquarters and Secretary of the meeting, the notes regarding this topic were as follows.

The meeting was presented with information on a research activity concerning network-wide trajectory planning in a TBO, which was in relation to the question how to balance individual flight efficiency/stability and network efficiency/stability in the TBO environment (WP/740 TBO next steps refers). The meeting noted that the aim of the research, by means of a Master Thesis at the Faculty of Aerospace Engineering at the Delft University of Technology, was to propose a suitable network-wide trajectory planning (NWTP) mechanism which uses the full potential of the technical enablers and processes implemented in a TBO environment. After seeking clarifications on the scope and focus of the study, and assumptions and tools used, the meeting noted that the research was well-headed in responding to one of challenges that need to be addressed for the successful implementation of the global TBO concept.

7

Conclusions

To accommodate the fast growing air traffic in a safe and efficient way, an ATM paradigm shift from current Time Based Operations towards Trajectory Based Operations (TBO) is envisioned. TBO entails the exchange, maintenance and use of consistent aircraft 4D trajectory (4DT) and flight information for collaborative decision-making on the flight. Collaborative means involvement of the airspace user (AU).

This thesis addresses a key research gap in the field of TBO, namely, balancing flight efficiency and network stability in a TBO environment. The balancing is done by a network-wide 4D trajectory planning algorithm (NWTP). In state of the art literature covering NWTP in TBO, two gaps could be identified. First, no AU perspective is taken into account in NWTP. Second, the full potential of the 4DT information is not used [18].

The thesis scope is limited to the mid-term planning phase of the demand-capacity balancing / traffic-synchronisation concept component. This phase lasts from days before departure until hours before departure, and the assumption is made that no flights considered for optimisation are airborne yet. Therefore, their trajectories could be fully modified from departure until arrival. Furthermore, only the en-route flight phase is considered. Additional mechanisms are needed for other flight phases. Lastly, uncertainties (e.g. weather changes, military airspace closures or take off time changes due to technical failures) are not taken into account.

A stable network is a network that converges towards an optimal solution. An optimal solution could be defined as a set of efficient flight trajectories which are not interacting with each other. Therefore, a balancing mechanism should be able to guarantee stability while it maximises efficiency. The flight efficiency indicator which takes into account the AU perspective is the trajectory modification cost (TMC). It is assumed that the initial filed flight plan (FPL) entails the most optimal trajectory. Without uncertainties, the network stability indicator is defined by the amount of trajectory interactions (TI) within the network. An interaction of trajectories occurs when separation standards between two trajectories are infringed in the mid-term planning phase. The objective of the planning problem is therefore to resolve the TIs with minimum TMC (in terms of fuel and delay).

To use the full potential of 4DT info in TBO, multiple decision variables could be used (in contrast to today's situation where only one decision variable, departure delay, is considered). The two decision variables used in this thesis to resolve interactions are departure delay and flight level change. Therefore, the constraints in the planning problem are maximum allowed departure delay per flight and maximum allowed flight level change per flight.

Today's FPLs are used in the case study, as future FPLs (eFPLs) are not available. Today's FPLs are relatively limited in terms of information compared to eFPLs, as the latter will provide more detailed 4DT information (e.g. waypoints, wind speed and direction). Linear interpolation is used to fill the missing waypoints. Before the optimisation, the FPL data is cleaned, and the coordinates are transformed from WGS84 into the Lambert Conformal Cone projection. Subsequently, the NWTP consists of two main processes, namely trajectory interaction detection (TID) and trajectory interaction resolution (TIR).

The TID process is based on the grid-based hash table method which uses a hash-table data structure that allows to quickly detect the number of interactions within a grid by only checking neighbouring cells of all points without considering full pairwise comparisons. It is therefore, a promising method when dealing with large data-sets [27].

The TIR process uses a metaheuristic, genetic algorithm (GA), to optimise as this is the most promising option due to the potentially fast and constant runtimes it brings [18], and the ability to scale computation, with increased solution quality or decreased runtime as a result [31]. The GA method is inspired by the process to drive biological evolution. The algorithm modifies a population of individual solutions, selects fittest and random individuals to be parents, and uses them to produce the children for the next generation, until converged towards the optimal solution.

The performance of the proposed algorithm is tested on a European network-wide case study with one hour of air traffic on a busy day (29 June 2018). 4440 flights were considered within this scope, of which 2364 were interacting. The TID algorithm is able to detect all interactions within $121.9s$. The TIR algorithm, however, was only able to resolve 79% of all initial interactions for a population of 20 chromosomes over 25 generations within $23h\ 29min\ 2s$. This is relatively slow as balancing mechanisms for current ATM environment such as the Computer Assisted Slot Allocation algorithm optimise the network in seconds [54]. One has to note however, that current balancing is done on macroscopic level (demand-capacity balancing), while the proposed algorithm balances on microscopic level (trajectory optimisation within network). Therefore, tests were conducted on a smaller volume for 100 generations to see whether the algorithm is able to resolve all TIs with minimum TMC. This characteristic is proven to be working, as TMC reduce over time after TIs are resolved.

A sensitivity analysis is performed to see the effect of a cost parameter change on performance. Neither the amount of interactions resolved within 25 generations nor the TIR/TID runtime are changed. Compared to the base case, the departure delay is selected more often as a result of the departure cost decrease. To verify the model, multiple processes and techniques were used to assure the model matches specifications and assumptions with respect to the model concept. Furthermore, to validate the NWTP approach and to see whether it meets the specifications, the methodology and preliminary results were proposed to a panel of experts, the ICAO ATMRPP 34 Working Group. The panel concluded the research was well-headed in responding to the challenge on how to balance individual flight efficiency/stability and network efficiency/stability in the TBO environment which needs to be addressed for the successful implementation of the global TBO concept.

As elaborated in the next chapter, future work could focus on improving performance of the algorithm in terms of quality and runtime (e.g. optimisation of GA parameters), improving relevance by decreasing assumptions and simplifications (e.g. addition of uncertainties), and broadening the scope (e.g. addition of departure phase).

8

Future work

To continue the research in the field of NWTP in a TBO environment, the chapter contains recommendations for future improvements. The improvements are divided into the three groups listed below.

- *Improve performance of algorithm in terms of quality and runtime.*

  To improve runtime performance, alternative optimisation methods such as Simulated Annealing with hill-climbing for optimisation [1] instead of the GA could be tested. Another option would be to explore the effect of distributed computing on the GA [31]. The fitness evaluation of each individual could be processed on a different core of a multi-core processor many computers have today. As a result the computing time spent on fitness evaluation for the entire population could be divided by the amount of cores. To improve quality of the solution, the parameters of the genetic algorithm (selection rate, mutation rate, crossover rate, population size and generation size) could be optimised to increase convergence to the optimum. Furthermore, an algorithm could be introduced which automatically extends individual flight stability limitations after no convergence towards a solution has been found for a certain amount of generations.

- *Improve relevance of algorithm by decreasing assumptions and simplifications.*

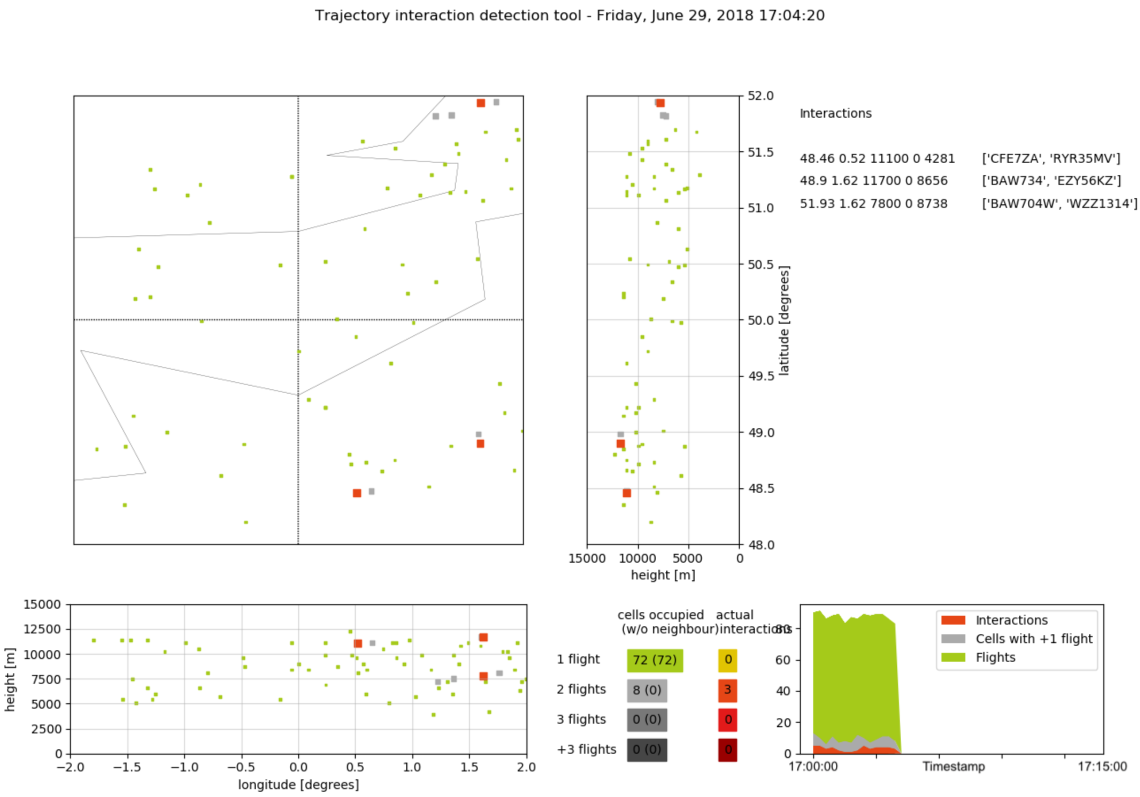
  Constraints due to other flights were considered only in the algorithm of this thesis. However, other constraints such as airspace closures for military exercises could be added. The impact of these airspace closures in a TBO environment could be analysed. Furthermore, uncertainties such as weather [1] could be taken into account. Full TBO is expected to be implemented by 2035. Forecasts could be used to extract filed FPLs of this moment in the future, to see how the algorithm would perform with future traffic volumes. BADA is updated regularly with new APMs. The algorithm could be triggered in the future with updated APMs (e.g. BADA 4) to see what the effect is of the assumption for replacing APMs of missing aircraft with the APM of an A320.

- *Extend completeness of algorithm by tackling out of scope problems.*

  Additional TIR strategies such as vectoring, airspeed change, negative delay, or temporary flight level changes could be added to extend completeness. Furthermore, past ATC conflict resolution strategies could be used to decide on future interaction resolution strategies in similar situations. The assumption that the filed FPL is optimal could be changed by flying great-circle distances is optimal. The effect could be investigated. Applicability of the algorithm for other planning phases (e.g. short-term, long-term) could be be examined. Furthermore, additional scenarios such as rounds of new entry FPLs during optimisation could be investigated. Also, other phases within the flight envelope such as take off, climb, descent and landing phases could be added. Following on this extension, if applicable more TI criteria such as time separation could be added. In addition, one could investigate the effect of optimising TMCs of an entire combined airline fleet instead of optimising for individual flights. Lastly, one could investigate how equity could be managed in TBO, as TBO enables a more systematic and measurable approach to manage equity (e.g. market based prioritisation, delay points)

A

Trajectory Interaction Detection Visual

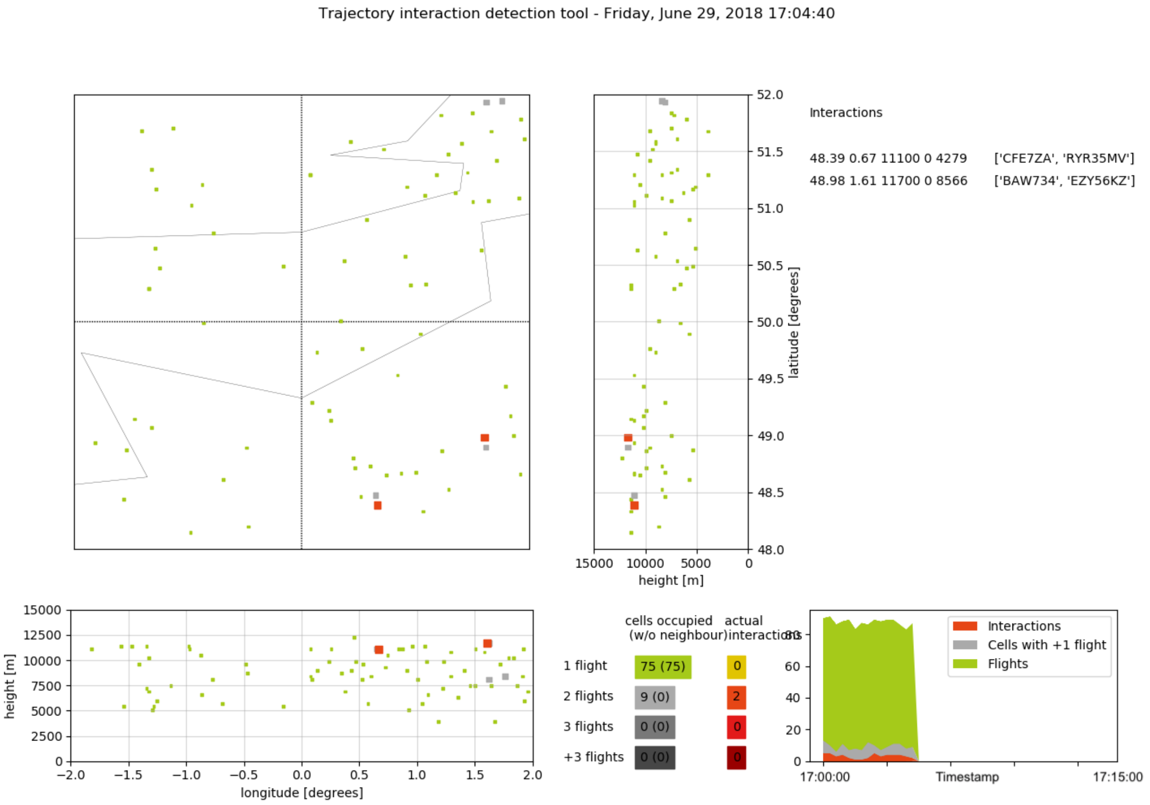

Trajectory interaction detection tool - Friday, June 29, 2018 17:04:20

Interactions

```
48.46 0.52 11100 0 4281      ['CFE7ZA', 'RYR35MV']
48.9 1.62 11700 0 8656       ['BAW734', 'EZY56KZ']
51.93 1.62 7800 0 8738       ['BAW704W', 'WZZ1314']
```

	cells occupied (w/o neighbour)	actual interactions
1 flight	72 (72)	0
2 flights	8 (0)	3
3 flights	0 (0)	0
+3 flights	0 (0)	0

Figure A.1: Small area case: network wide trajectory interaction detection visual (17h04h20).



Interactions

48.39 0.67 11100 0 4279 ['CFE7ZA', 'RYR35MV']
48.98 1.61 11700 0 8566 ['BAW734', 'EZY56KZ']

	cells occupied (w/o neighbour)	actual interactions
1 flight	75 (75)	0
2 flights	9 (0)	2
3 flights	0 (0)	0
+3 flights	0 (0)	0

Figure A.2: Small area case: network wide trajectory interaction detection visual (17h04h40).

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